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GRINDSTONE FLAT AND BIG FLAT EXCLOSURES — A 41-YEAR RECORD OF CHANGES IN CLEARCUT ASPEN COMMUNITIES

W.F. MUEGGLER and D.L. BARTOS

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RESEARCH SUMMARY

Deer browsing prevented aspen regeneration in both uncut stands and small 1/20-hectare clearcuts, even though nearby large burns regenerated successfully. Size of the clearcut or burned area may be critical in determining success of aspen regeneration; areas less than about 2 hectares in size may adversely concentrate deer use. Shrub production was less under deer use and forb production was less under cattle use than on protected areas. More aspen suckers were produced in uncut stands where cattle grazed than in stands protected from grazing, suggesting a possible relationship between sucker initiation and reduced competition from the herbaceous understory. Removal of aspen cover changed herbaceous composition from forb to grass dominants and discouraged conifer invasion.

PREFACE

Opportunities sometimes exist to gain considerable insight into long-term effects of management on vegetation by remeasuring old administrative studies and exhuming from the files data collected during the early stages of the study. Such was the case with the Grindstone Flat and the Big Flat deer and cattle exclosures discussed in this report. A few days spent collecting current data and in perusing old files have permitted us to trace the influence of clearcutting and of deer and cattle on plant succession in two stands of aspen over a period of 41 years.

We wish to acknowledge the contribution of the Fishlake National Forest personnel involved in establishing the plots and in gathering data over the decades. H. M. Christensen apparently was instrumental in starting the study in 1934. Data were collected by R. J. Costley, and W. E. Augsbach in 1937, by W. L. Robinette in 1942, and by E. R. Doman, and O. Julander in 1949. A rough-draft report prepared by E. R. Doman, D. I. Rasmussen, and H. M. Christensen in 1959 provided helpful background information on the area and assisted interpretation of the early data.

SETTING

Beaver Mountain is a high plateau on the Fishlake National Forest in southern Utah that rises to more than 3,650 m (12,000 ft) elevation at its highest points. Large expanses of aspen *(Populus tremuloides)* dominate the elevations between 2,400 and 3,000 m (8,000 to 10,000 ft). Mixed stands of spruce *(Picea engelmannii)* and fir *(Abies lasiocarpa)* are common on northerly exposures and at higher elevations. Many large grassy openings intermixed with the aspen and conifer communities contribute to the diversity of vegetation types. Historically this area has been important summer range for both deer *(Odocoileus hemionus)* and livestock.

Deer apparently were abundant in about 1865 when Beaver County was first settled, for the pioneers had little difficulty keeping themselves supplied with venison. Soon after settlement, the summer ranges on Beaver Mountain were heavily stocked with sheep and cattle. Livestock overgrazing and unrestricted hunting apparently caused deer numbers to decline to a low from 1900 to 1910. The combined effect of placing Beaver Mountain under National Forest administration in 1906 with better regulation of forage use and the enactment of a "buck law" by the Utah legislature in 1913 with enforcement of hunting regulations permitted the deer populations to increase markedly. Excessive use of aspen suckers and palatable shrubs by 1926 was attributed to high populations of deer. By 1934, aspen regeneration was poor over large areas of Beaver Mountain. Overuse of the summer range coincided with overuse of browse on adjacent winter ranges on both the east and west sides of Beaver Mountain. As a result, antlerless deer hunts were begun in 1934 to control population numbers.

Overuse of the livestock summer range on Beaver Mountain was recognized as a serious problem in the early 1930's. Cattle and sheep, as well as the deer, were considered too numerous. Overgrazing in the extensive aspen type was of particular concern. Proposed reductions in livestock grazing were protested by ranchers who blamed the deer for depleted forage conditions. This dispute resulted in the establishment of study plots on aspen range within cattle allotments to demonstrate the relative effects of deer and cattle grazing on the forage and on aspen regeneration.

APPROACH

Two sets of plots were located in aspen types on the Beaver District of the Fishlake National Forest. One set was established near the lower edge of the aspen zone at about 2,590 m (8,500 ft) elevation on Grindstone Flat (sec. 29, T. 29 S., R. 4 W.); the other set was placed near the upper edge of the aspen zone on Big Flat (sec. 18, T. 29 S., R. 4 W.) at about 3,200 m (10,500 ft) elevation. Each set of plots consisted of about a 30- by 60-m (100- by 200-ft) deer exclosure where the vegetation was protected from use by all ungulates, an adjacent area of like size that excluded livestock but was open to deer use, and an adjacent area open to use by both deer and livestock. Three-fourths of each exclosure was clearcut of aspen; the aspen was left intact in the remaining fourth. The areas were cut and pole fences constructed in the fall of 1934.

Aspen sprouts and other vegetation were first measured in 1937, 3 years after the plots were established. A single, permanent 23.8-m^2 (4.88- by 4.88-m; 16- by 16-ft) quadrat was established on the cleared and uncleared portion of each exclosure and on the range adjacent to the exclosures. Vegetation canopy cover below 1.68 m (5-1/2 ft) in height was determined for each species on these quadrats. In addition, individual stems of trees and shrubs on the quadrats were counted. Vegetation measurements on these quadrats were repeated in 1942, in 1949, and in 1975. Such measurements enable tracing the sequence of successional change after cutting and of change attributable to protection from grazing.

Measurements confined to a single 4.88- by 4.88-m quadrat provided a restricted and questionable overall sample of treatment effects. Consequently, we expanded our sampling in 1975 to include estimates of productivity and composition of understory vegetation and counts of aspen numbers by size-class distribution over the entire treatment plots. Understory production was determined from three sets of five 1/2-m^2 quadrats randomly distributed over each treatment plot. The current year's biomass for plants on each of four quadrats was estimated as a percent of the fifth; the fifth was then clipped to ground level, dried, and weighed. The percentage estimates were then converted to weights and the average of the 15 quadrats converted to kilograms dry weight per hectare. Biomass composition by vegetation class and by individual species was estimated for each five-quadrat set and averaged for each treatment. Aspen and conifer trees were counted by size classes on a 0.0202-hectare (1/20-acre) strip within each treatment. Trees representing different size classes in each treatment were then cored and aged.

Reliable data on changes in deer and cattle grazing pressure on the study sites over the 41-year period are not available. We know, however, that judicious management dictated reduction in numbers of both species from their high levels early in the century. We also know that the general area continued to support substantial numbers of deer and cattle over the study period. Interpretation of vegetation differences between treatments is therefore based upon the presence or absence of cattle versus deer use rather than on absolute changes in animal numbers.

EVALUATION

Understory vegetation at the Grindstone Flat site near the lower edge of the aspen zone is appreciably different from that at Big Flat near the upper edge of the aspen zone. For example, shrubs are fairly abundant in the aspen understory at Grindstone Flat, but are lacking at Big Flat. The two areas, therefore, cannot be considered true replications for evaluating treatment effects on understory vegetation. However, those species common to both areas might be expected to respond similarly to like treatments.

Although each study site at Grindstone and Big Flat appeared to be environmentally uniform, the vegetation was not sampled before clearcutting or exclosure construction to verify uniformity between treatment plots. Consequently, we must assume that subsequent differences in vegetation between plots on a site result from treatment effects and not from initial dissimilarities in vegetation between plots.

RESPONSE OF TREES

In 1975, the oldest aspen measured at Grindstone Flat was 172 years old (40.6 cm d.b.h., 17.4 m in height); the oldest at Big Flat was 126 years (35.3 cm d.b.h., 15.2 m in height). Thus, the stands were at least 131 and 85 years old, respectively, when the study began in 1934. We also found trees on both areas that were between 30 and 60 years old in 1934. Judging from the concern about lack of aspen regeneration in the early 1930's, we can assume that few trees were less than 30 years old on the study sites in 1934. Apparently very few of the aspen suckers that arose between 1905 and 1934 were able to escape browsing and become trees.

The persistent occurrence of suckers over the years despite animal use is evidenced by the number of suckers in 1975 less than 0.5 m tall on the uncut plots continually used by deer and cattle (table 1). Under continued use, approximately 7,000 suckers per hectare occurred at Grindstone Flat and 26,000 per hectare at Big Flat. Most of these suckers were heavily utilized. In 1942 and in 1949, approximately 3,000 suckers (less than 1.68 m in height) per hectare occurred on the Grindstone Flat plots and 14,000 to 30,000 per hectare occurred on the Big Flat plots in these years, respectively (table 2). Judging from the lack of aspen reproduction in the 0.5 m tall to 5.1-cm d.b.h. size class on these grazed plots in 1975 (table 1), few of these suckers were able to escape and become saplings.

Table 1.--*Numbers of aspen and conifers by size classes on the Grindstone and Big Flat plots in 1975, 41 years after establishment.*

Size class	Grindstone Flat					Big Flat				
	Uncut			Cut		Uncut			Cut	
	Closed to use	Deer use only	Deer and cattle use	Closed to use	Deer use only	Closed to use	Deer use only	Deer and cattle use	Closed to use	Deer use only
	Number/0.0202 hectare transect									
<0.5 m tall										
Populus tremuloides	19	10	[1]145	16	6	142	47	525	116	0
Conifers[2]	9	6	28	9	1	15	21	27	9	3
0.5-2 m tall										
P. tremuloides	37	8	0	89	0	92	0	1	87	0
Conifers	4	9	13	6	5	32	31	14	16	6
2 m tall-<5.1 cm d.b.h.										
P. tremuloides	60	0	0	45	0	118	5	8	251	0
Conifers	5	5	6	2	1	16	6	6	4	4
5.1-10.2 cm d.b.h.										
P. tremuloides	63	20	22	173	0	20	19	18	28	0
Conifers	4	6	4	6	0	4	0	6	0	1
10.2-15.2 cm d.b.h.										
P. tremuloides	22	12	45	8	0	4	9	18	0	0
Conifers	3	0	3	1	1	0	0	2	0	1
15.2-20.3 cm d.b.h.										
P. tremuloides	6	5	19	0	0	3	7	3	0	0
Conifers	0	4	3	1	1	0	0	0	0	0
20.3-25.4 cm d.b.h.										
P. tremuloides	1	0	2	0	0	4	7	6	0	0
Conifers	0	0	3	0	0	0	0	0	0	1
25.4-30.5 cm d.b.h.										
P. tremuloides	1	0	1	0	0	1	0	0	0	0
Conifers	0	1	0	0	0	0	0	0	0	1
>30.5 cm d.b.h.										
P. tremuloides	0	2	6	0	0	0	0	0	0	0
Conifers	0	0	0	0	0	0	0	0	0	0

[1] Almost all were heavily utilized.

[2] Approximately 90 percent of conifers at Grindstone Flat were *Abies lasiocarpa*; at Big Flat, approximately 70 percent were *A. lasiocarpa*, and 30 percent were *Picea engelmannii; Pinus albicaulis* and *Pseudotsuga menziesii* also occurred.

As expected, clearcutting greatly stimulated production of aspen suckers. The third growing season (1937) after cutting, the ungrazed clearcut plot had approximately 26 times as many suckers as the ungrazed uncut plot at Grindstone Flat, and approximately 19 times as many at Big Flat (table 2). By 1942, 8 years after cutting, such large differences were no longer apparent. Many of the suckers on the ungrazed clearcut either grew into saplings or were reduced by natural thinning (fig. 1A). By 1975, over three-fourth of the aspen stems on the ungrazed clearcut plots at both areas were over 0.5 m tall, and approximately 60 percent were over 2 m tall (table 1, fig. 1B).

Table 2. -- [illegible]

Location and species	1957 Number of stems	1957 Canopy cover	[illegible] Number of stems	[illegible] Canopy cover	[illegible] Number	[illegible]	[illegible]	[illegible]
		[illegible]		Percent		Percent		
UNCUT								
CLOSED TO USE								
Grindstone Flat								
Populus tremuloides	14	12.2	81	17.1		6.4	1	
Rosa woodsii	75	[1] --	156	6.3	10[illegible]		[illegible]	1.0
Symphoricarpos vaccinioides	--	5.5	--	6.8	[illegible]	10.8	77	
Big Flat								
P. tremuloides	9	4.1	54	7.9	63	1.4		5.5
DEER USE ONLY								
Grindstone Flat								
P. tremuloides	28	2.2	11	.1	[illegible]	[illegible]	[illegible]	.4
R. woodsii	84	.1	71	.9	75		23	1.2
S. vaccinioides	14	12.9	--	9.2	[illegible]	17.0	[illegible]	
Big Flat								
P. tremuloides	--	1.1	--	.1	39	1	34	2.9
DEER AND CATTLE USE								
Grindstone Flat								
P. tremuloides	0	0	7	.3	7	[illegible]		
R. woodsii	91	.1	161	1.8	1[illegible]			
S. vaccinioides	1	1.2	[illegible]	1.5	[illegible]	1.1	[illegible]	
Big Flat								
P. tremuloides	41		34	[illegible]	71	.1		1.4
CUT								
CLOSED TO USE								
Grindstone Flat								
P. tremuloides	369	63.8	113	40.5			[illegible]	2.5
R. woodsii	54	.4	81	[illegible]				
S. vaccinioides	-	11.8	--	17.7				
Big Flat								
P. tremuloides	170	51.9	151	50.2				14.1
DEER USE ONLY								
Grindstone Flat								
P. tremuloides	12	6.6	[illegible]	0				
R. woodsii	[illegible]	[illegible]	55	.5				
S. vaccinioides	5	2.0	1[illegible]	[illegible]				1.[illegible]
Big Flat								
P. tremuloides	17	.2						

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[1] A dash indicates missing data.

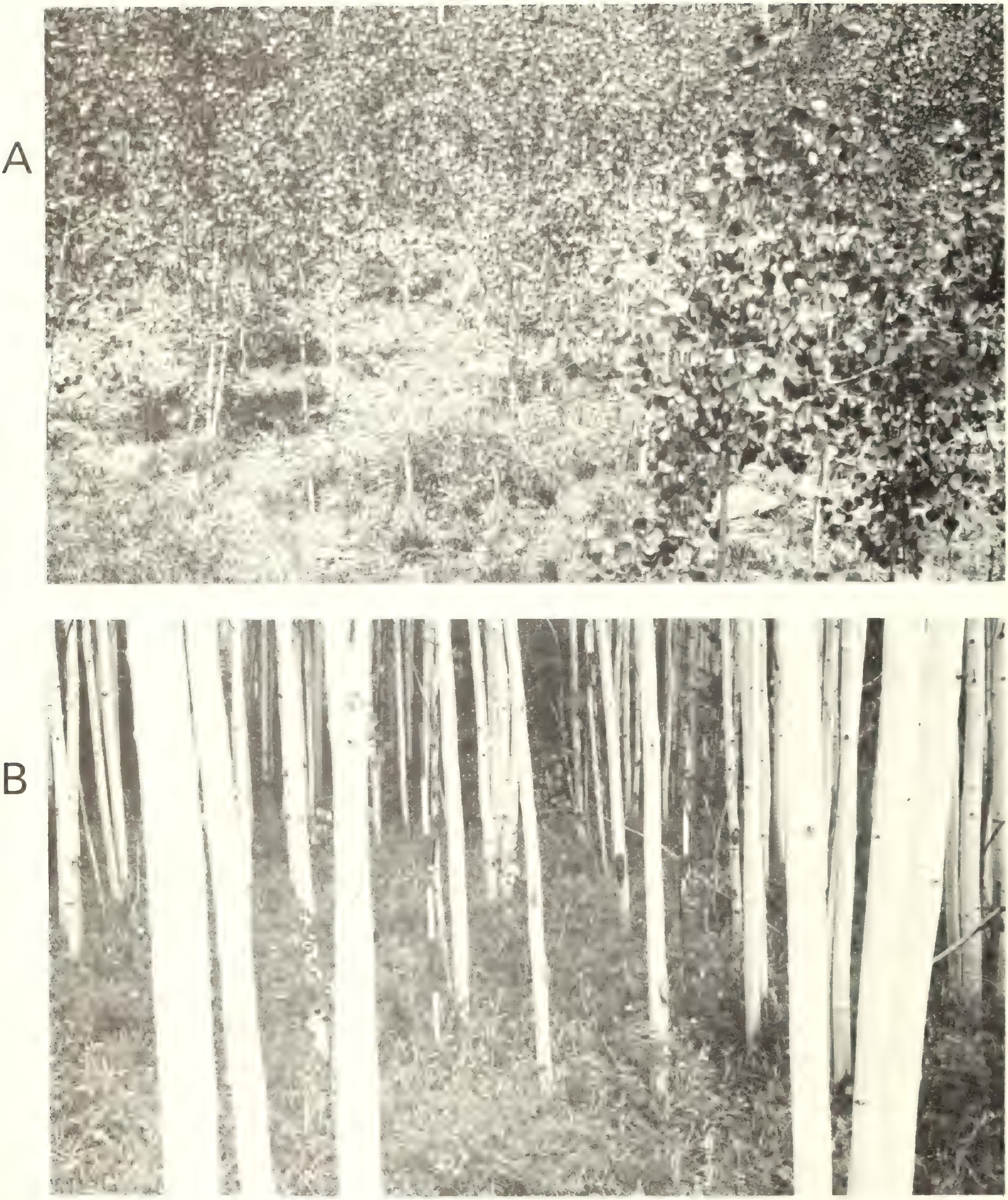

Figure 1.--The clearcut area at Grindstone Flat protected from all ungulate use showing (A) amount of reproduction in 1942, 8 years after cutting, and (B) subsequent development of the aspen stand by 1975, 41 years after cutting.

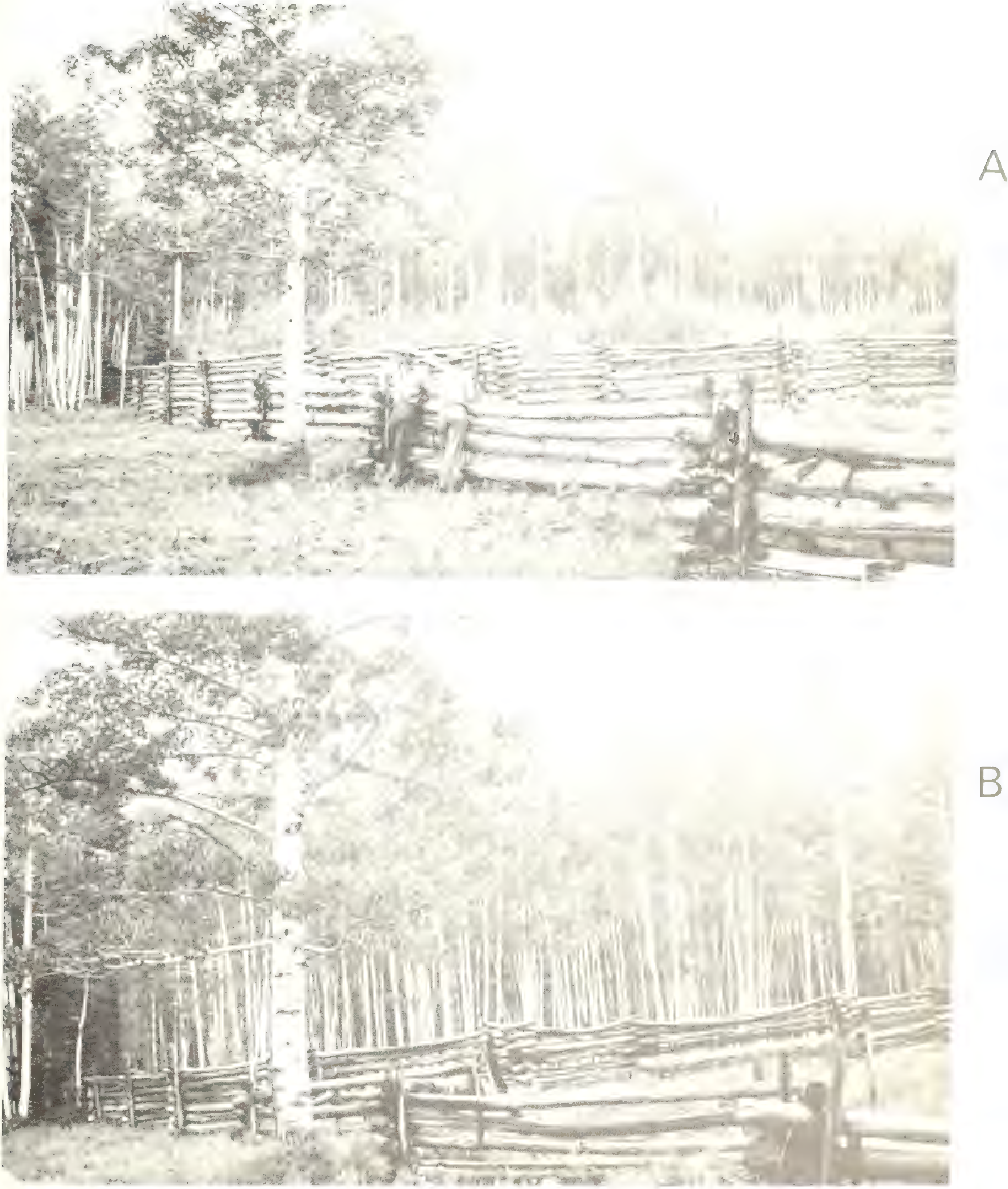

Figure 2.--The Grindstone Flat [illegible] area open to deer use only, and clearcut closed to all ungulate use. Note the original uncut aspen stand in the background of figure 2A.

Although we have no record of sucker production the first two growing seasons after clearcutting, we have no reason to believe that initial stimulation of sucker production would differ between the plots open and closed to deer use. By 1937, the effect of deer use on sucker mortality in the clearcuts was strikingly evident (table 2); the plot open to deer use at Grindstone Flat had only 3 percent as many suckers as the protected plot and the one at Big Flat had only 10 percent as many suckers as the protected plot. By 1942, neither the Grindstone nor the Big Flat clearcut plots used by deer contained either aspen suckers or aspen saplings (fig. 2A). The extensive data collected in 1975 (table 1) show that, although a few small suckers were found on the cut plot open to deer at Grindstone Flat, none were found at Big Flat.

Some aspen suckers still arose at the edges of the clearcuts adjacent to the uncut plots and adjacent to the cut but protected plots that contained 40-year-old trees. Invariably, these suckers were heavily browsed by deer and remained less than about 30 cm tall. Suckers were seldom found more than about 4 m from the edge of the cut. A striking exception was an aspen tree, approximately 10 cm d.b.h. that grew well into the grazed clearcut at Grindstone Flat. This tree was enclosed by 1 m tall wire net fencing. Apparently, the tree was enclosed as a sucker and so escaped browsing.

Generally, aspen suckers were able to develop into saplings and perpetuate the aspen stands on these small plots only when protected from deer browsing (fig. 2). This was true for both the cut and uncut plots at both Grindstone and Big Flats. Despite deer use, small suckers continued to occur in uncut stands, but were invariably suppressed by heavy browsing. In contrast, suckers were usually present in grazed clearcuts for only a few years after cutting, probably because the small, heavily browsed suckers were unable to keep alive the extensive root system (the sucker source) of the cut trees.

Approximately 10 times as many small suckers continued to occur on the uncut plots used by both deer and cattle as on those used by deer alone (table 1). This might be related to reduced herbaceous understory where cattle grazed (table 3). Competitive relationships might have been altered sufficiently to stimulate aspen suckering.

Deer and cattle use apparently did not directly affect the success or persistence of conifer regeneration. However, conifer reproduction appeared considerably more successful in those stands with an aspen overstory than those without (fig. 3). In 1975, the clearcut, but regenerated aspen plots, contained over 2 times as many conifers less than 10.2 cm d.b.h. as those clearcut plots without an aspen overstory (table 1). Thus, deer use can indirectly impede conifer establishment by preventing a clearcut from going back to aspen cover. This lends credence to the belief that aspen commonly serves as a nurse crop for conifers. The plots at Big Flat contained almost 1-1/2 times as many conifers as those at Grindstone Flat, but this is attributed primarily to elevational and seed source differences.

RESPONSE OF BROWSE

Aspen reproduction less than 1.68 m in height constitutes the primary browse at both Grindstone Flat and Big Flat; aspen foliage above this level is not considered available to deer. Snowberry (*Symphoricarpos vaccinioides*) and rose (*Rosa woodsii*) are important browse species on Grindstone Flat, but such shrubs are lacking on Big Flat. Thus, ample aspen reproduction is critical both for maintaining viable aspen stands and as a source of browse for deer.

Table 3.--[illegible]

Understory vegetation	Grindstone Flat									
	Uncut									
	Closed to use	Deer use only	Deer and cattle use	[illegible]	[illegible]	use	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL	714	920	[illegible]	978	1,474	[illegible]	1,024	[illegible]		[illegible]
Shrubs	228	74	24	[illegible]	[illegible]	[illegible]		0		
Graminoids	21	340	94	68	[illegible]	101	[illegible]	[illegible]	17	[illegible]
Forbs	464	506	274	831	590	742	952	212		[illegible]
SHRUBS										
Berberis repens		4	1							
Rosa woodsii	2	T	1	T	T					
Symphoricarpos vaccinioides	30	4	4	8	8					
GRAMINOIDS										
Agropyron [illegible]	T	[illegible]	1	1	[illegible]			T		
Bromus anomalus	2	30	17	2	2	2	5	[illegible]	1	[illegible]
Carex spp.	T	T	1	1		[illegible]	1	2	3	3
Festuca idahoensis						[illegible]	1	20	[illegible]	
Poa fendleriana		3			7	T	T		1	[illegible]
Sitanion hystrix		T		T	[illegible]					
Stipa comata				1	18					
Stipa lettermani	1	2	4		20					
Stipa occidentalis						[illegible]				
FORBS										
Achillea lanulosa	T	2		1	1	T				
Agoseris glauca					T					
Astragalus bourgovii	3	T	[illegible]	2			[illegible]	20		
Castilleja linariaefolia	10	T	T	12		[illegible]				
[illegible]	18	20	12	15	4	T				
Erigeron speciosus	1	5			22	T				
Fragaria americana	T	3	4	5	T		[illegible]	[illegible]		1
Frasera speciosa	12	T				[illegible]		10		1
Helenium hoopesii	T				T	[illegible]	[illegible]	10		[illegible]
Helianthella uniflora	8	T		[illegible]	1					
Lupinus leucophyllus	5	20	[illegible]	[illegible]	7	57				
Potentilla pulcherrima	1	T	1	[illegible]	2	3				
Smilacina stellata	7		[illegible]							
[illegible]										
Taraxacum officinale	T	2				1				
Thalictrum fendleri		T	T	[illegible]						
Other herbs	T	1	T	T	T					

In the mid-1930's, aspen reproduction under 1.68 m tall was scarce on Grindstone Flat. The 1937 data from the uncut plot open to cattle and deer use, however, indicated that suckers still occurred with some abundance at Big Flat (table 2). The amount of aspen browse on these uncut areas open to use by both cattle and deer did not change appreciably over the years. Even the relatively numerous aspen suckers on the 23.8 m quadrat at Big Flat in 1975 (over 10,000 per hectare) did not provide much more than 1 percent crown cover. This suggests that even though sprouting ability persisted over the years, the small and spindly sprouts provided relatively little browse.

Barring cattle, but not deer, somewhat benefited aspen browse production. After 41 years of deer use only, crown coverage of aspen browse was about 3 percent on Big Flat, but still less than one-half percent on Grindstone Flat.

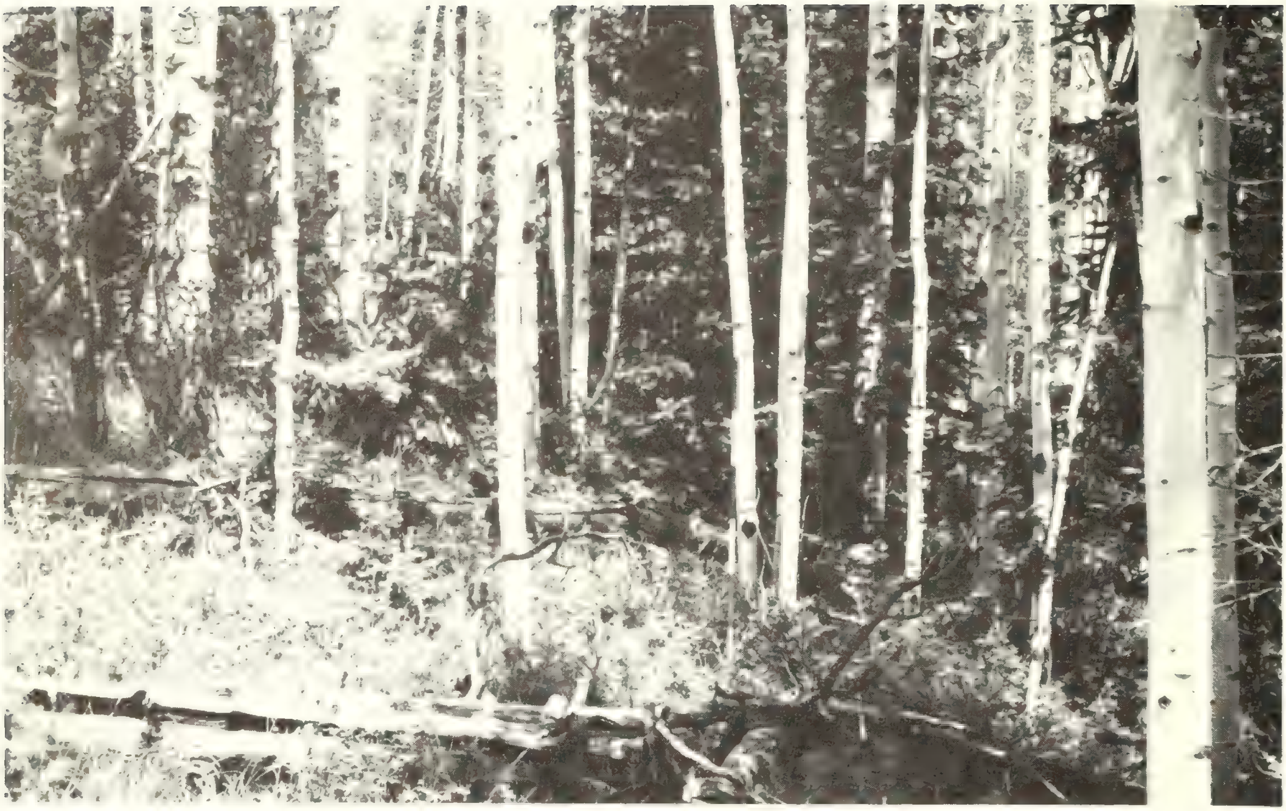

Figure 3.--Conifer invasion under an uncut aspen stand at Grindstone Flat in 1975.

Eliminating both cattle and deer use on the uncut areas apparently enabled both sucker numbers and aspen foliage to increase for 10 to 15 years following protection (table 2). Browse production then declined as the aspen suckers grew above the 1.68-m available browse height. After 41 years of protection from grazing, aspen browse covered over 5 percent of the Big Flat plot and over 2 percent of the Grindstone Flat plot. Although foliage mass was greater on the protected than on the grazed plots, sucker numbers were not. This suggests that the protected suckers were large and vigorous, whereas the suckers on the grazed plots, though perhaps more numerous, were small and weak.

The amount of rose and snowberry on the permanent quadrats fluctuated greatly over the years under all grazing and cutting treatments (table 2). However, the extensive data obtained in 1975 (table 3) indicate that deer use of the uncut stands markedly reduced both of these shrubs, particularly the snowberry.

RESPONSE OF UNDERSTORY VEGETATION

The single 4.88- by 4.88-m permanent quadrat placed in each treatment and sampled over the years provided a very restricted and probably invalid sample of response on each area because of initial dissimilarity of vegetation on these small quadrats (tables 4 and 5). We believe the extensive 1975 production inventory (table 3) gives a more precise account of species response to grazing treatment as identified by differences accumulated over the 41-year period. The 1975 production inventory is therefore used as a main indicator of species response to grazing, with the permanent quadrats used to provide supplementary information on successional changes. Additionally, only the

Table 1.--[illegible]

Understory vegetation	Closed to [illegible]					[illegible]						
	1937	1942	1944	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UNCUT												
Total shrubs and trees	25	15	[illegible]	[illegible]	[illegible]	[illegible]						
Total graminoids	37	[illegible]	[illegible]	4	[illegible]	[illegible]	[illegible]					
Total forbs	38	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
Abies lasiocarpa	T		[illegible]	[illegible]		1			[illegible]			
Achillea lanulosa				1	1	[illegible]	[illegible]	[illegible]			5	1
[illegible]					T	[illegible]	[illegible]		1			
Astragalus bourgovii	T		[illegible]		[illegible]	[illegible]	1			11		
Bromus anomalus	5	[illegible]	4			1	1	[illegible]				
Carex spp.	6	7	4		25		10					
Castilleja linariaefolia		1	4	2								
Cirsium undulatum	1	2	2	15	2							
Erigeron speciosus	2		1	[illegible]	1							
Fragaria americana				1								
Frasera speciosa		T		[illegible]	1	1	1	[illegible]				
Helianthella uniflora		T	1	15								
Lupinus leucophyllus	20	14	21	[illegible]		[illegible]	[illegible]		1			11
Poa fendleriana	20	4	1		2	13	4	T	T		T	
Populus tremuloides	9	27	12	5	8	T	3	1		1	T	
Potentilla pulcherrima	3	6	4	3	1	T	T	1				
Rosa woodsii	12	4	2	1	5	T	4	1			1	
Stipa spp.	5	5	17	3	6	5	30	5			[illegible]	
[illegible]	4	12	17		[illegible]	[illegible]	[illegible]	[illegible]				
Taraxacum officinale	10	6	1	1	15	3	T	3	1	2	T	
Thalictrum fendleri									2	3	1	
Others	3	1	[illegible]	5	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	
CUT												
Total shrubs and trees	75	65	--	15	10	10	-	[illegible]				
Total graminoids	15	15	--	4	[illegible]	[illegible]		[illegible]				
Total forbs	10	[illegible]	--	53	40	[illegible]		[illegible]				
Abies lasiocarpa		[illegible]	--	4								
Achillea lanulosa												
[illegible]												
Astragalus bourgovii	1	1	-	[illegible]	[illegible]	1						
Bromus anomalus	4	5			[illegible]	[illegible]						
Carex spp.	8	[illegible]		T	[illegible]							
Castilleja linariaefolia	[illegible]		--	5	[illegible]	1						
Cirsium undulatum		1		16		1						
Erigeron speciosus	T		[illegible]									
Fragaria americana	T	1										
Frasera speciosa		[illegible]	--	11								
Helianthella uniflora												
Lupinus leucophyllus	4	[illegible]		[illegible]	[illegible]	10						
Poa fendleriana	1	3	--		10	10						
Populus tremuloides	68	40	-									
Potentilla pulcherrima	2	[illegible]	[illegible]	4	2							
Rosa woodsii	[illegible]	3		1	2							
Stipa spp.	1	1	--		3	6						
[illegible]	5	20		6		1						
Taraxacum officinale	[illegible]	5		1	20							
Thalictrum fendleri												
Others	4	1	--	[illegible]		[illegible]		[illegible]				

---

[1] A dash indicates missing data.

Table 5.--*Changes* [illegible] *1.68 m in height on permanent* [illegible] *m²* [illegible] *g flat between 1937 (3 years following establishment) and 1975.*

Understory vegetation	Closed to use				Deer use only				Deer and cattle use			
	1937	1942	1949	1975	1937	1942	1949	1975	1937	1942	1949	1975
UNCUT												
Total shrubs and trees	10	40	50	51	5	20	5	20	2	25	45	45
Total graminoids	50	25	15	5	35	35	55	22	52	35	35	15
Total forbs	40	35	35	44	60	45	40	58	46	40	20	40
Abies lasiocarpa	1	10	15	30	T	18	5	12	T	22	40	25
Achillea lanulosa	5	10	7	T	7	22	18	15	5	12	5	5
Agropyron caninum												
Astragalus bourgovii					24	15	15	10	10	10	5	6
Bromus anomalus												
Carex spp.	4	4	4	1	17	7	14	1	2	5	T	
Festuca idahoensis	45	18	10	4	17	15	24	5	50	28	34	15
Fragaria americana	22	5	1	3	24	5	6	7	25	10	5	6
Frasera speciosa	T	T	5	15			T	T			T	12
Helenium hoopesii	4	8	T	T					1	5	3	1
Lupinus leucophyllus			6	15				25				8
Picea engelmannii	T	10	10	1							T	5
Poa fendleriana					T	8	5		T	2	T	T
Populus tremuloides	10	20	25	20	5	2	T	8	2	3	5	15
Potentilla pulcherrima	T	3	4	2	T	2	T		T	1		T
Solidago decumbens	7	7	12	1	4		T		2		1	1
Stipa lettermani	1	3	1		T	2	1				T	
Taraxacum officinale	T	2	T					T				
Others	2	T	T	8	2	4	12	17	3	2	2	1
CUT												
Total shrubs and trees	50	55	[1]--	67	1	1	--					
Total graminoids	25	20	--	9	55	80	--	69				
Total forbs	25	25	--	24	44	19	--	31				
Abies lasiocarpa			--	5		T	--					
Achillea lanulosa	2	15	--	T	T	2	--	8				
Agropyron caninum	T		--		T	3	--	7				
Astragalus bourgovii			--				--					
Bromus anomalus			--	T			--					
Carex spp.	1	3	--	2	1	2	--	2				
Festuca idahoensis	23	15	--	7	54	70	--	45				
Fragaria americana	16	3	--	6	37	3	--	T				
Frasera speciosa	T	T	--	8		T	--					
Helenium hoopesii		T	--		1	3	--	15				
Lupinus leucophyllus			--	3			--	6				
Picea engelmannii			--			T	--					
Poa fendleriana			--				--					
Populus tremuloides	50	55	--	50	1		--					
Potentilla pulcherrima	1	1	--	T	2	2	--	T				
Solidago decumbens	1	1	--	2			--	T				
Stipa lettermani	1	2	--			5	--	15				
Taraxacum officianle	4	4	--	T	4	9	--	T				
Others	1	1	--	17	T	1	--	2				

A dash indicates missing data.

uncut areas were compared to evaluate response of understory vegetation to grazing. Response of the cut areas is confounded by the initial elimination of aspen overstory by cutting and subsequent maintenance of the grazed openings through destruction of aspen suckers by deer. With the exception of aspen, species differences on the cut areas are more likely a result of continued lack of aspen competition than of direct utilization by deer.

The most striking difference in understory attributable to animal use was the great reduction in total shrubs (table 3). After 41 years, the ungrazed area at Grindstone Flat produced almost 10 times more shrubs than the area grazed by both cattle and deer and over 3 times more than that grazed just by deer. The graminoids increased under grazing at Grindstone Flat, but not at Big Flat. On both sites, cattle use apparently hampered total forb production, but deer use did not. Overall production of understory herbage was greatest on the areas closed to cattle, but grazed by deer. Deer browsing may tend to reduce the aspen overstory sufficiently to promote production of understory herbs, yet forb use by cattle appears to hinder overall understory production.

Most of the decrease in shrub production on the grazed areas can be attributed to the large reduction in snowberry. Of the graminoids, the sedges (*Carex* spp.) apparently decreased, but the presumably palatable fringed brome (*Bromus anomalus*) increased unexpectedly and appreciably on the grazed plots. Of the forbs, western yarrow (*Achillea lanulosa*) and milkvetch (*Astragalus bourgovii*) increased greatly under grazing, particularly where grazed by cattle. Velvet lupine (*Lupinus leucophyllus*) increased during the 41-year period on all of the permanent quadrats except on the uncut, ungrazed area on Grindstone Flat (tables 4 and 5). Production of both Wyoming painted-cup (*Castilleja linariaefolia*) and oneflower helianthella (*Helianthella uniflora*) was conspicuously reduced by deer use. Showy frasera (*Frasera speciosa*) appeared to be harmed by grazing at Grindstone Flat, but not at Big Flat.

Clearcutting aspen directly affected the abundance of certain understory species by altering light and moisture availability. An insight into environmental requirements of certain species can be gained by comparing the clearcut areas maintained as openings by deer browsing aspen reproduction and those that reverted to a dense stand of pole-size aspen (tables 3, 4, and 5). The effect of deer use on different plant species in the maintained openings can be discounted by examining the effect of deer use on the uncut areas.

Eliminating aspen cover greatly benefited the grasses, somewhat improved shrub production, and caused a decrease in production of forbs. As aspen reproduction developed into a dense pole-size stand on the protected clearcuts, cover of grasses declined and forbs increased.

The grasses responding most positively to removal of aspen cover were Idaho fescue (*Festuca idahoensis*) and the needlegrasses (*Stipa* spp.). Slender wheatgrass (*Agropyron caninum*), mutton bluegrass (*Poa fendleriana*), and bottlebrush squirreltail (*Sitanion hystrix*) also increased with clearcutting.

The only forbs that appeared to directly benefit by removal of aspen cover were Oregon fleabane *(Erigeron speciosus)* and orange sneezeweed *(Helenium hoopesii)*. Although velvet lupine increased on most areas, it increased less in the openings than in the closed stands, suggesting that lupine is favored by shade. Virginia strawberry *(Fragaria americana)*, on the other hand, declined on all areas over the 41-year period, but mostly in the openings, suggesting that it too is favored by shade. Fendler meadowrue *(Thalictrum fendleri)* also was favored by an aspen overstory. Interestingly, wavyleaf thistle *(Cirsium undulatum)* apparently was favored by aspen removal at Big Flat, but by a closed overstory at Grindstone Flat. This is not unreasonable for the 600-m elevational difference between the two areas could appreciably alter the insolation and available moisture relationships for this species.

MANAGEMENT IMPLICATIONS

Extrapolating results from these two small exclosure studies to broad management units is hazardous, particularly where animal behavior is involved. The exclosure results suggest that aspen reproduction on Beaver Mountain is doomed because of current levels of deer browsing. This is not true. The error of such a conclusion is readily demonstrated by ample reproduction of aspen on extensive burns within a few miles of the exclosures (fig. 4). Apparently, aspen suckers were so abundant over hundreds of hectares of mixed aspen and conifer stands that burned in 1958 that combined deer and livestock use did not hamper successful reestablishment of the aspen stands. Presumably, as these rejuvenated aspen stands mature and become less dense, ungulate use may again be sufficient to prevent survival and growth of the new suckers that periodically occur.

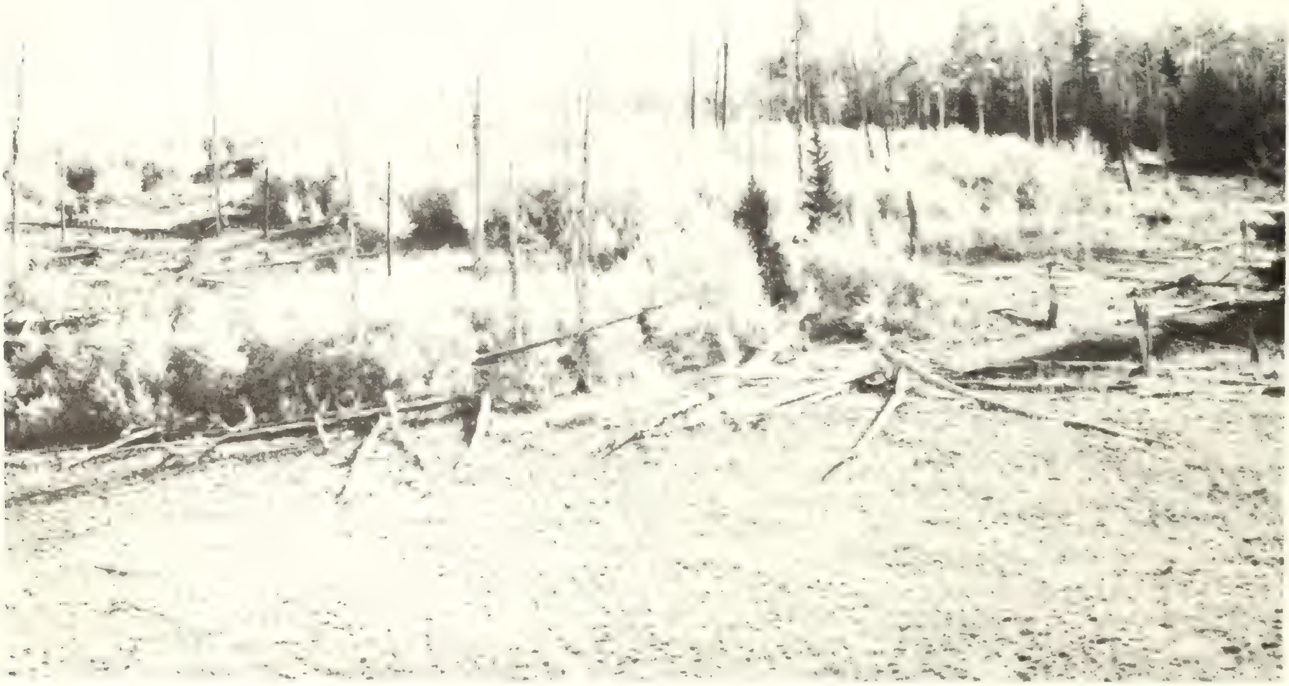

Figure 4.--A large 600-hectare area near Grindstone Flat burned in 1958 had ample aspen regeneration in 1975.

Sampson (1919) found that moderate use by cattle does not appreciably harm aspen reproduction in either standing timber or on clearcuts, but that sheep grazing can be very destructive unless it is light. Smith and others (1972) concluded from a study of four scattered sites in Utah that proper livestock management, especially management of sheep, is essential for regeneration of aspen following clearcutting or burning. They also concluded that the normal deer populations during the period of their study (1961 to 1969) had little effect on development of aspen reproduction in large clearcuts. Jones (1975) found that widespread and "appreciable" elk browsing of aspen reproduction on a 2-hectare clearcut in Arizona did not prevent establishment of a new aspen stand. On our study areas, however, deer use in both standing timber and in small clearcuts apparently was enough to keep suckers from developing into saplings and so prevented successful regeneration.

We believe that successful reestablishment of aspen on clearcuts or burns may be dependent upon the size of area treated, unless deer and livestock use can be rigidly controlled. Without control of ungulate use, clearcutting or burning less than about 5 hectares of mature aspen might be futile. Even if livestock are excluded from such areas for from 5 to 10 years, deer may concentrate on the small treated areas and prevent escape of the sprouts. Smith and others (1972) indirectly recognized this possibility by recommending that sufficiently large acreages be cut to provide an excess of aspen forage.

Our data suggest that use of the herbaceous understory in standing timber by cattle may alter the vegetation-competition relationships sufficiently to reduce mortality of young aspen suckers. This proposal is supported by data from Sampson (1919) showing that about twice as many suckers occurred on moderately and heavily grazed plots as on lightly grazed plots. Abundance of sucker production, however, is no guarantee of successful regeneration. Continued survival and subsequent growth of the suckers is affected by the intensity of ungulate browsing and rodent activity disease incidence in wounded stems, as well as dieback from undetermined causes. Schier (1975) observed that such sucker dieback is common even in vigorous aspen clones.

A prounounced shift in species composition of the understory vegetation from forbs to grasses can be brought about by clearcutting aspen stands. This difference presists until the aspen overstory reforms and creates conditions more favorable for the forbs. Shrub production benefits somewhat by aspen removal, but not as much as the grasses do. If aspen suckers are not suppressed by browsing, succession back to forb dominance of the understory may occur within 10 years. Otherwise, the grasses will remain abundant as long as an aspen overstory fails to develop--unless, of course, the grasses are overgrazed by cattle.

In extensive areas of aspen, greater habitat diversity and improved forage conditions for both livestock and wildlife might be created by clearcutting small, scattered 2- to 5-hectare openings. These openings would favor the production of grasses for cattle and, at least for the first few years, aspen suckers as browse for deer. Deer utilization of the suckers in these small openings would prevent reestablishment of aspen and thus prolong grass production for cattle. Ideally, such openings would be created as part of an aspen timber sale program where a market for aspen products exists.

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ESTIMATING MERCHANTABLE VOLUME AND STEM RESIDUE N FOUR TIMBER SPECIES:

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odgepole pine
Western larch
Douglas-fir

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USDA Forest Service
Research Paper INT-196
November 1977

ESTIMATING MERCHANTABLE VOLUME AND STEM RESIDUE IN FOUR TIMBER SPECIES:

Ponderosa pine
Lodgepole pine
Western larch
Douglas-fir

James L. Faurot

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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RESEARCH SUMMARY

Presents tables and equations for estimating total cubic volumes of wood, wood residue, and bark for ponderosa pine, lodgepole pine, western larch, and Douglas-fir. Tables represent second-growth trees 80 years old or less, ranging in size from 1-1/2 inches d.b.h. to the maximum diameter measured for the respective species. The equations and tables provide a means for estimating wood and bark residue volumes from tops, bole sections, and smaller submerchantable stems. Tables and equations can also be used to estimate total cubic volume for the size classes, species, and locale sampled.

INTRODUCTION

Estimates of tree volume, based on diameter, height, and species, provide the foundation for many forestry practices. Recent interest in volumes of forest residues, rapidly changing utilization practices, and an accelerated need to manage second-growth stands of timber have created a demand for tables that indicate not only the volume of wood in the merchantable part of a stem, but also the volumes of wood and bark in the nonmerchantable parts, and in stems smaller than the prevailing merchantability standard.

The accompanying tables (appendix) have been prepared mainly for the purpose of predicting stem residue volumes that may result from thinning or harvesting. The trees selected for the study do not exceed 80 years of age, and so may represent stem development in unmanaged second-growth stands. Minimum tree diameter is 1-1/2 inches d.b.h. (o.b.) and the maximum diameter varies by species, given the constraints of age and growing site. The sample trees were obtained from selected stands on both public and private lands in western Montana and include a broad range of growing conditions. Only dominant and codominant trees were measured, and no trees were selected that showed, from ring examination, marked periods of suppression.

METHOD OF STEM MEASUREMENT

All measurements were made on felled trees as shown in figure 1. The total height nd d.b.h. (o.b.) of each tree were determined first. To eliminate the problems of isproportionate measure in using a fixed bolt length, the tree was then divided into ix segments of equal length for further measurement. A diameter tape was used to easure diameter outside bark at the base of each segment. Bark thickness at the base f each segment was measured using a Swedish bark gage. At thick-barked section the ark gage measurement was augmented with an axe cut, the thickness then measured with n engineer's scale. A minimum of three bark-thickness measurements were made at the ase of each segment and the average value was determined. An additional measurement, nside bark, was made at an assumed stump height of 1 foot above the average ground evel. All diameter and bark-thickness measurements were recorded to the nearest tenth f an inch. Total tree height was measured to the nearest foot. The segment lengths ere converted to inches and measured to the nearest inch.

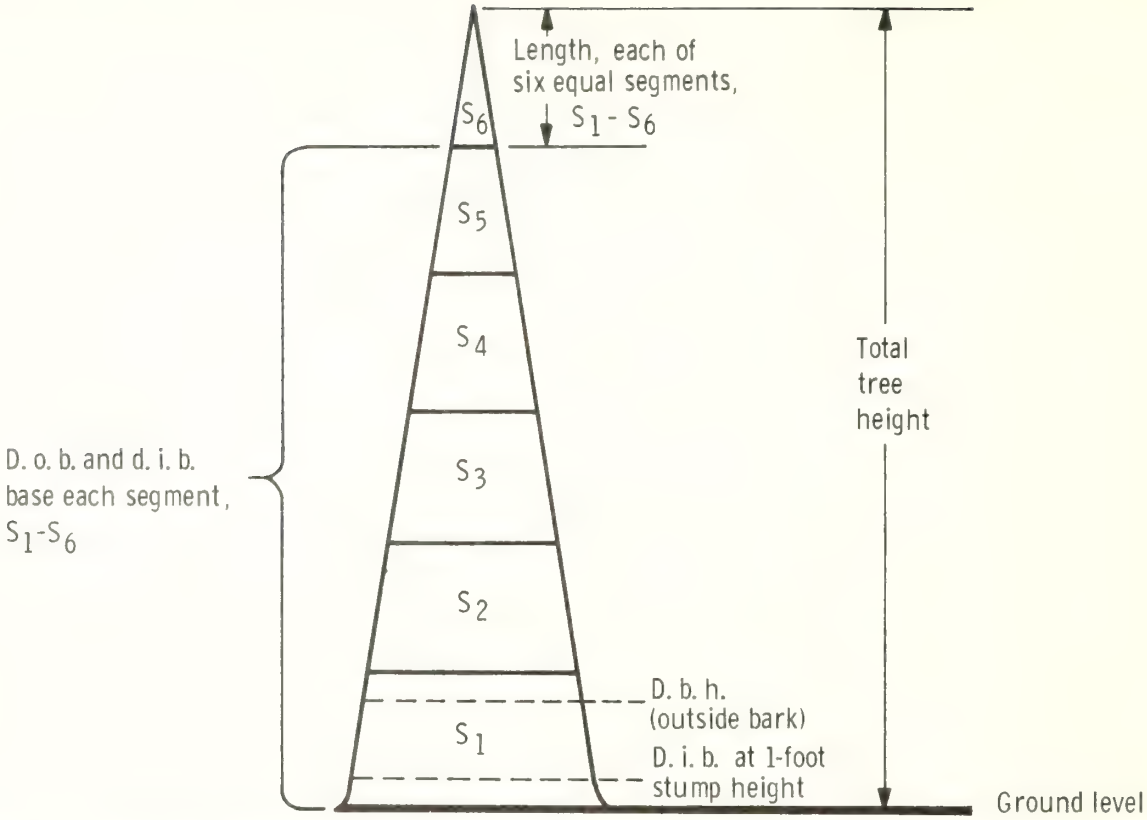
Length, each of six equal segments, $S_1 - S_6$
S_6
S_5
S_4
S_3
S_2
S_1
Total tree height
D. o. b. and d. i. b. base each segment, S_1-S_6
D. b. h. (outside bark)
D. i. b. at 1-foot stump height
Ground level

Figure 1.--Stem measurements that describe diameter and height for each sample tree. Designated segments, s_n, divide the total tree height into six equal segments.

BASIC VOLUME COMPUTATION PROCEDURES

Stem Total Wood Volume

The volume of the middle four truncated segments of each tree was obtained by trea ing the segments as a cone frustrum, while the top segment was treated as a cone. The volume of the base segment was obtained by calculating the stump volume as a truncated cone and adding it to the remaining segment volume. The inside bark diameter was obtained by subtracting double bark thickness from d.o.b. All segment and tree volumes were developed from a computer program specifically written for the data. The volumes were calculated in cubic feet for the entire stem, inside bark, including the stump and top.

Top Volume Above a Specified Diameter

Top volume is defined as the volume, inside bark, of that portion of the stem above a specified minimum top d.i.b., ranging from 2 to 8 inches. For trees in which the specified minimum top diameter occurs low in the tree (for example, an 8-inch minimum top diameter in a 9-inch d.b.h. tree), top volume is further limited to that portion of the stem above an 8-foot bole section. Utilization of at least an 8-foot section above the stump is assumed, regardless of diameter.

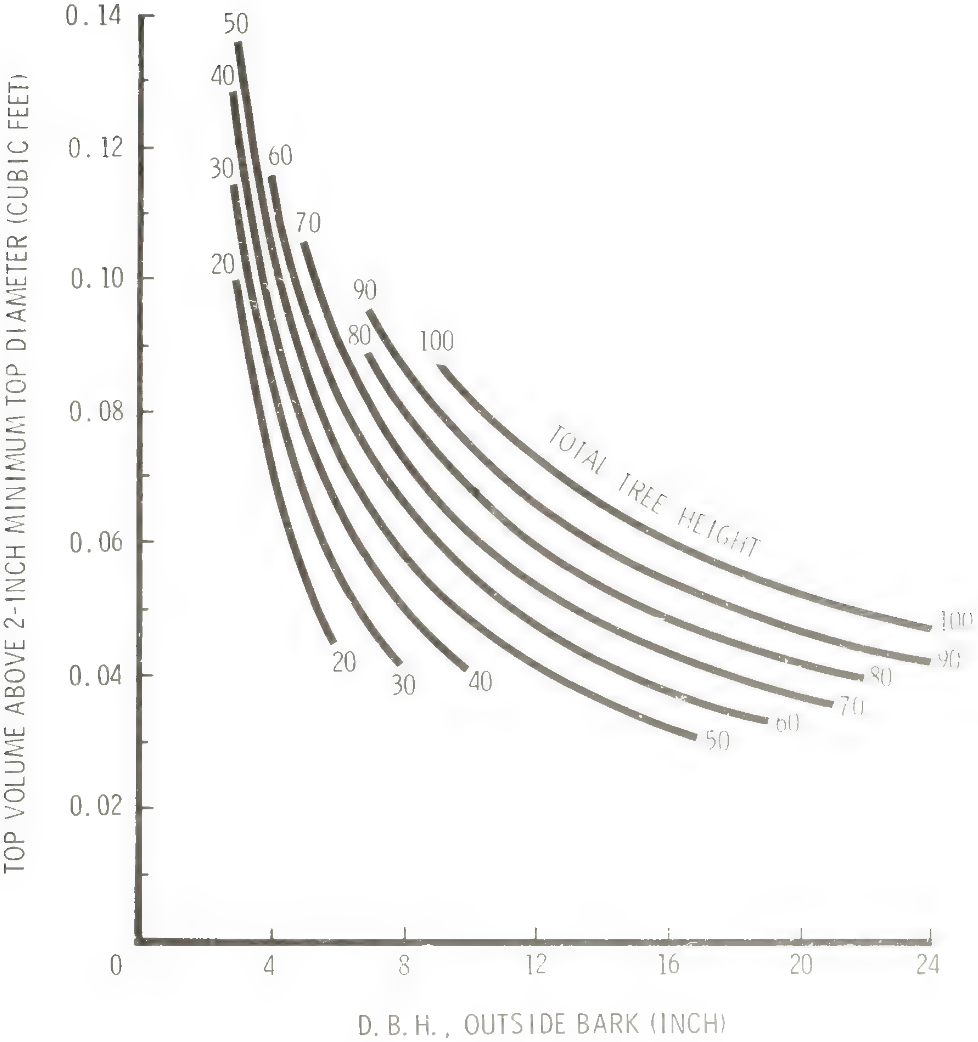

Figure 2.--Top volume, defined as the volume above a specified minimum diameter, varies with diameter of the tree and total height of the tree. Illustrated is the relationship between these variables for ponderosa pine.

Top volumes were calculated by means of the same computer program that was used to alculate total stem volumes. Using the segment diameters and bark thicknesses recorded or the tree, the minimum top-diameter position on the stem was calculated. Volumes of ll full segments above this point, plus the volume of a partial segment immediately bove minimum top diameter, were aggregated to determine top volume. Top volume is a unction of tree diameter and height, as illustrated in figure 2.

Bark Thickness

Bark thickness was obtained using the measured values as recorded from the field ample. However, because of the excessively thick bark at the tree base, only the easurements of the upper five segments were used.

Gross Bark Volume

Gross bark volume is defined as the bark volume for the entire stem without allowance for fissure or void volume. The value was obtained for each tree by subtracting the volume inside bark from the volume outside bark. The volume in each case was calculated in the manner previously described for the calculation of stem volume. Because d.o.b. at stump height was not obtained during the field measurements, that particular value was estimated from the bark-thickness equations developed for each species.

Stump Diameter — D.B.H. Relationship

The relationship between diameter at stump height, i.b., and diameter at breast height, o.b., was obtained for each tree using the information obtained from field measurements.

METHODS OF REGRESSION MODEL CONSTRUCTION

The development of the models for table construction proceeded in four steps: (1) selection of the independent variables, (2) graphic analysis, (3) regression analysis, and (4) final selection of the model.

Development of Tables

The regressions and resulting tables were prepared specifically to make use of measurements that are commonly obtained under field conditions. With this in mind, diameter breast height, outside bark (d.b.h., o.b.), and total height were used as fundamental independent variables for all stem, top, and bark volume estimates. Diameter outside bark was used to predict bark thickness, again because of the relative simplicity of field measurements. Stump diameter, i.b., one of the measurements taken during the data collection, was used as the independent variable in developing the d.b.h.-stump diameter equations.

Random samples, varying from 10 to 20 percent of the total number of observations in each data set, were drawn for graphic analysis. These analyses provided insights for the selection of the form of the variables, from which one or more models were postulated. Stepwise, least squares multiple regression techniques, using the improvement in the "F" statistic as a delimiter, were used to develop the models. When more than one model seemed statistically appropriate, an examination of the residuals was helpful in selecting the final model.

With the exception of the stand volume equations, all volume predictions incorpora logarithmic models. Logarithmic expressions for the estimation of tree stem volume have been widely used since 1933, when the method was proposed by Schumacher and Hall (1933). Investigators in other fields have likewise found the procedure useful (Baskerville 1972; Zar 1968).

Two characteristics are common when describing functional relationships between tree or stem size and volume. First, these relationships are nonlinear; and second, the variation within size classes is neither constant nor directly proportional to tree size. When the data are plotted on logarithmic paper, the form may appear as a straight line with a reduced heterogeneity of variance. The coefficients of the resulting log linear model can be estimated by the method of least squares.

To provide comparative statistics, the tables incorporating logarithmic models include expressions of mean error, average bias, and average deviations, all expressed in percentage. These expressions indicate the relative reliability of the tables with which they are associated.

Percent average is obtained as follows:

$$100(\Sigma\ Yi - \Sigma\ Yi)/\Sigma\ Yi = 100\ (\hat{Y} - Y)/\bar{Y}$$

where $\Sigma\ Yi$ = sum of arithmetic estimates

$\Sigma\ Yi$ = sum of observations

$\hat{Y}$ = mean of arithmetic estimates

$\bar{Y}$ = mean of observations

Mean error, expressed in percentage, is an indication of the average variation of the sample. Expressing the deviation in percentage tends to overcome the inherent problem of heterogeneous variance. The procedure for calculating the mean error is:

$$\left[\sum_{i=1}^{n} \Big((Yi - Yi)100/Yi\Big)^2/n-k-1\right]$$

where Yi - observed value

Yi = arithmetic estimated value

n - number of observations in the data set

k = number of independent variables in the model

nasmuch as bias is included in the calculation, the value obtained is always somewhat arger than if an unbiased procedure had been used initially. From an interpretive tandpoint, the percent mean error is analogous to the usual standard error (deviation) f regression.

Although not appropriate from a purely statistical sense, average percent deviation rovides an estimate of the average deviation of the individual observations from their espective means. In the past the value has often accompanied volume tables to provide he user with a rough indication of variability. Average percent deviation is always ess than mean error, being approximately 75 percent that of mean error, depending upon he magnitude of bias. Average deviation equals

$$\sum_{i=1}^{n} \left(\left|(Yi - Yi)100/Yi\right|\right)/n$$

Development of Stand Volume Tables

Stand volume tables are usually developed from multiple-stand samples. The tables included here are based upon single-stem volume equations which, when extended, provide the tabular values. The procedure used in the development of the equations consisted of regressing total stem volume against the product of basal area and total height for each tree. The intercept term was dropped and the regression coefficient was used as an estimate of cylindrical form factor. Because the form factor decreases with increasing d.b.h., the factor used to develop the tables represents those trees in the diameter class interval of 4 to 10 inches. The tabular values are obtained by the formula:

$$V = KBH$$

where V = total stand volume

K = form factor

BH = basal area of the stand multiplied by the average height of the trees sampled for basal area.

The factors for the four species are:

Species	*Factor*
Ponderosa pine	0.36
Western larch	.36
Douglas-fir	.40
Lodgepole pine	.46

The only published stand volume tables existing for the species and locale involved in this study are for lodgepole pine (Cole 1971). A comparison between the two tables shows remarkable agreement, suggesting that the approach used here is worthy of application for the other species until such time as conventional stand volume tables are developed.

TABLES FOR VOLUME ESTIMATION

The Tables

In the appendix of this paper, volume estimation tables are presented for four species--ponderosa pine, lodgepole pine, western larch, and Douglas-fir. In all tables, diameter classes indicated are based on midpoint measurements; e.g., the 6-incl class includes trees 5.5 through 6.4 inches in diameter. The tables include:

1. *Standard volume tables:*--These tables contain estimates of total gross cubic-foot wood volume for the entire stem, inside bark, including stump and top. They are intended for use as standard volume tables.

2. *Top volume tables.*--Top volume tables are included for specified minimum top diameters, inside bark, from 2 to 8 inches. Top volume refers to total gross cubic-foot wood volume of the portion of the stem above the specified diameter. Additionally, where specified minimum top diameter approaches tree d.b.h., top volume is limited to that portion of the stem above an 8-foot "merchantable" stem section.

3. *Gross bark volume tables.*--Gross bark volume is the total cubic-foot volume of bark for the entire stem, including stump and top, without reduction for void space.

4. *Double bark thickness tables.*--These tables are included to aid in the estimation of wood and bark residue contained in pieces of the stem, rather than the entire stem or top. The estimates are based upon the inside and outside bark field measurements of the upper five tree segments.

5. *Stump diameter-d.b.h. relationship tables.*--These tables indicate the relationship between stump diameter, inside bark, and tree diameter at breast height, outside bark. They are useful in reconstructing stem or stand parameters from stump measurements.

6. *Stand volume tables.*--These tables contain estimates of the total cubic-foot volume of a stand (or component of a stand, such as a given story in a multistoried stand) in cubic feet per acre, for basal area and dominant tree average height corresponding to the stand or stand component for which basal area was obtained.

Applications and Limitations

Tables of the kind represented here are empirically developed, and the tabular values are estimated averages for each size class. The fact that the values are averages suggests that the tables are appropriate only when applied to relatively large numbers of observations within the range of the source data. The tabular values have been extended approximately two diameter and height classes beyond the range of the sample data. Extrapolation beyond the data range is ill advised, particularly toward the upper limits of the diameter classes because of the limited number of trees represented in those classes.

Users of the stand volume tables should be aware that, in multistoried or in mixed stands, volumes can be obtained by identifying and measuring each stand component, then summing these partial volumes to obtain the estimated total volume.

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Table 1.--Total cubic volume, inside bark, including stump and top--ponderosa pine

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - -	- - -	- - -	- - -	- - -	- - -	*Cubic feet*	- - -	- - -	- - -	- - -	- - -	- - -	*No. trees*
2	0.17	0.23	0.30	0.40	0.53	0.70								21
3	0.40	0.52	0.67	0.86	1.11	1.44								22
4	0.72	0.92	1.17	1.49	1.89	2.41	3.06							38
5		1.44	1.81	2.28	2.86	3.59	4.50	5.65						23
6		2.08	2.59	3.22	4.00	4.97	6.17	7.67						12
7		2.84	3.50	4.31	5.31	6.54	8.06	9.93	12.25					12
8		3.72	4.54	5.56	6.79	8.31	10.16	12.42	15.19					13
9			5.72	6.95	8.44	10.25	12.45	15.13	18.37	22.32				15
10			7.05	8.49	10.25	12.38	14.94	18.05	21.79	26.31				20
11			8.47	10.17	12.22	14.67	17.62	21.17	25.42	30.54				12
12				12.00	14.34	17.14	20.49	24.49	29.27	34.98	41.81			23
13				13.97	16.62	19.78	23.53	28.00	33.32	39.64	47.17			17
14				16.05	19.05	22.58	26.75	31.70	37.56	44.51	52.74	62.49		20
15				18.33	21.64	25.54	30.14	35.58	42.00	49.57	58.51	69.06		24
16				20.72	24.37	28.66	33.71	39.64	46.62	54.83	64.48	75.84		23
17				[illegible]	27.23	31.94	37.44	43.88	51.43	60.28	70.65	82.80		21
18					[illegible]	[illegible]	41.33	48.28	56.41	65.91	77.00	[illegible]		13
19					[illegible]	[illegible]	45.38	[illegible]	61.71	71.71	83.33	97.29		12
20						42.70	49.59	57.00	66.00	77.70	90.34	104.81		12
21						[illegible]	[illegible]	[illegible]	71.80	83.85	97.12	[illegible]	130.20	1
22						[illegible]	[illegible]	[illegible]	78.05	90.17	104.17	120.54	139.62	2
23							[illegible]	[illegible]	83.87	96.67	111.34	[illegible]	147.80	2
24								[illegible]	89.85	103.54	118.77	[illegible]	156.94	0

[illegible] 1.3[illegible] [illegible]
[illegible]
[illegible]

[illegible] error = [illegible] percent
Bias = [illegible] percent
Precision = [illegible] percent

Table 2.--*Top cubic volume, inside bark (2-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													*No. trees*
3	0.077	0.099	0.114	0.126	0.136	0.145								19
4	0.052	0.071	0.085	0.096	0.106	0.115	0.123							38
5		0.055	0.068	0.078	0.088	0.097	0.105	0.112						23
6		0.045	0.056	0.066	0.075	0.084	0.091	0.098						12
7		0.037	0.048	0.058	0.066	0.074	0.081	0.088	0.095					12
8		0.032	0.042	0.051	0.059	0.067	0.074	0.080	0.087					13
9			0.037	0.046	0.053	0.061	0.067	0.074	0.080	0.087				15
10			0.034	0.041	0.049	0.056	0.062	0.069	0.075	0.081				20
11			0.030	0.038	0.045	0.052	0.058	0.064	0.070	0.076				12
12			0.029	0.035	0.042	0.048	0.054	0.061	0.066	0.072	0.078			23
13			0.026	0.033	0.039	0.045	0.051	0.057	0.063	0.069	0.074			17
14			0.024	0.030	0.037	0.043	0.049	0.054	0.060	0.066	0.071	0.076		20
15			0.022	0.028	0.035	0.040	0.046	0.052	0.057	0.063	0.068	0.073		24
16				0.027	0.033	0.038	0.044	0.049	0.055	0.060	0.066	0.071		25
17				0.025	0.031	0.037	0.042	0.047	0.053	0.058	0.063	0.068		21
18				0.024	0.030	0.035	0.040	0.046	0.051	0.056	0.061	0.066		13
19				0.023	0.028	0.033	0.039	0.044	0.049	0.054	0.059	0.064		12
20				0.022	0.027	0.032	0.037	0.042	0.047	0.052	0.057	0.062		12
21						0.031	0.036	0.041	0.046	0.051	0.056	0.061	0.666	4
22						0.030	0.035	0.040	0.044	0.049	0.054	0.059	0.064	2
23							0.034	0.038	0.043	0.048	0.053	0.057	0.062	1
24								0.037	0.042	0.047	0.051	0.056	0.061	0

Log V = -0.460586 -2.09688 (log D) +0.733094 (log D) (log H)
S.D. of coeff. 0.143811 0.0617454
S.E. = 0.08256

Mean error = 18.9 percent
Ave. bias = -2.4 percent
Ave. deviation = 14.3 percent

Table 3.--*Top cubic volume, inside bark (7-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	*cubic feet*	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	*No. trees*
4	0.241	0.323	0.383	0.432	0.475	0.513	0.547							28
5		0.241	0.294	0.338	0.377	0.412	0.445	0.475						22
6		0.190	0.237	0.277	0.312	0.345	0.375	0.404						12
7		0.155	0.197	0.233	0.266	0.297	0.325	0.352	0.377					12
8		0.130	0.168	0.202	0.232	0.260	0.287	0.312	0.336					13
9			0.146	0.177	0.205	0.232	0.257	0.281	0.304	0.326				15
10			0.129	0.158	0.184	0.209	0.233	0.256	0.278	0.299				20
11			0.115	0.142	0.167	0.191	0.213	0.235	0.256	0.277				12
12			0.104	0.129	0.153	0.175	0.197	0.218	0.238	0.258	0.277			23
13			0.094	0.118	0.140	0.162	0.183	0.203	0.222	0.241	0.260			17
14			0.086	0.109	0.130	0.151	0.170	0.190	0.208	0.227	0.245	0.263		20
15			0.080	0.101	0.121	0.141	0.160	0.178	0.197	0.214	0.232	0.249		24
16				0.094	0.113	0.132	0.151	0.168	0.186	0.203	0.220	0.237		25
17				0.088	0.106	0.125	0.142	0.160	0.177	0.193	0.210	0.226		21
18				0.082	0.100	0.118	0.135	0.152	0.168	0.184	0.201	0.217		13
19				0.078	0.095	0.112	0.128	0.145	0.161	0.176	0.192	0.208		12
20				0.073	0.090	0.106	0.122	0.138	0.154	0.169	0.184	0.200		12
21						0.101	0.117	0.132	0.147	0.163	0.177	0.192	0.207	4
22						0.097	0.112	0.127	0.142	0.156	0.171	0.186	0.200	2
23							0.107	0.122	0.136	0.151	0.165	0.179	0.194	1
24								0.117	0.132	0.146	0.160	0.174	0.188	0

log V = [illegible] -1.27765 (log D) + 0.09746 (log D)(log H)
S.D. of coeff. [illegible].14133 [illegible].05960
S.E. = 0.0744[illegible]

Mean error = 16.[illegible] percent
Avg. bias = -2.1 percent
Avg. deviation = 13.[illegible] percent

Table 4.--*Top cubic volume, inside bark (4-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													*No. trees*
5		0.770	0.910	1.025	1.124	1.212	1.291	1.364						12
6		0.600	0.723	0.825	0.914	0.994	1.067	1.134						11
7		0.486	0.595	0.687	0.768	0.841	0.908	0.971	1.029					12
8		0.405	0.502	0.586	0.660	0.727	0.790	0.848	0.903					13
9			0.433	0.509	0.577	0.640	0.698	0.753	0.804	0.853				15
10			0.379	0.449	0.512	0.571	0.625	0.676	0.725	0.772				20
11			0.336	0.401	0.460	0.515	0.566	0.614	0.660	0.705				12
12			0.301	0.362	0.417	0.468	0.517	0.562	0.606	0.648	0.689			23
13			0.272	0.329	0.381	0.429	0.475	0.519	0.560	0.601	0.640			17
14			0.247	0.301	0.350	0.396	0.440	0.481	0.521	0.560	0.597	0.633		20
15			0.227	0.277	0.324	0.367	0.409	0.449	0.487	0.524	0.560	0.595		24
16				0.257	0.301	0.343	0.382	0.420	0.457	0.493	0.527	0.561		25
17				0.239	0.281	0.321	0.359	0.395	0.431	0.465	0.498	0.531		21
18				0.223	0.263	0.301	0.338	0.373	0.407	0.440	0.472	0.504		13
19				0.209	0.248	0.284	0.319	0.353	0.386	0.418	0.449	0.480		12
20				0.197	0.234	0.269	0.303	0.335	0.367	0.398	0.428	0.458		12
21						0.255	0.288	0.319	0.350	0.380	0.409	0.438	0.466	4
22						0.242	0.274	0.305	0.334	0.363	0.392	0.420	0.447	2
23							0.261	0.291	0.320	0.348	0.376	0.403	0.430	1
24								0.279	0.307	0.334	0.361	0.388	0.414	0

Log V = 0.842466 -2.13641 (log D) +0.59070 (log D) (log H)
S.D. of coeff. 0.162516 0.065958
S.E. = 0.07579

Mean error = 17.1 percent
Ave. bias = -2.1 percent
Ave. deviation = 12.9 percent

Table 5.--Top cubic volume, inside bark (6-inch top diameter)--ponderosa pine

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													No. trees
6		1.390	1.674	1.910	2.116	2.301	2.470	2.626						2
7		1.113	1.362	1.572	1.757	1.924	2.078	2.221	2.355					11
8		0.918	1.139	1.328	1.496	1.648	1.789	1.921	2.046					13
9			0.973	1.145	1.298	1.438	1.568	1.691	1.807	1.917				15
10			0.846	1.002	1.143	1.273	1.394	1.508	1.616	1.720				20
11			0.744	0.888	1.019	1.139	1.253	1.360	1.462	1.559				12
12			0.663	0.796	0.917	1.030	1.136	1.237	1.333	1.426	1.515			23
13			0.595	0.719	0.833	0.939	1.039	1.134	1.225	1.313	1.398			17
14			0.539	0.655	0.762	0.862	0.956	1.046	1.133	1.217	1.298	1.376		20
15			0.492	0.600	0.701	0.795	0.885	0.971	1.054	1.134	1.211	1.286		24
16				0.553	0.648	0.738	0.823	0.905	0.984	1.061	1.135	1.207		25
17				0.513	0.603	0.688	0.769	0.848	0.923	0.997	1.068	1.138		21
18				0.477	0.563	0.644	0.722	0.797	0.869	0.940	1.008	1.076		13
19				0.445	0.517	0.605	0.679	0.751	0.821	0.889	0.955	1.020		12
20				0.417	0.495	0.570	0.641	0.711	0.778	0.843	0.907	0.970		12
21						0.538	0.607	0.674	0.739	0.802	0.864	0.924	0.984	4
22						0.510	0.576	0.641	0.703	0.764	0.824	0.883	0.941	2
23							0.548	0.610	0.671	0.730	0.788	0.845	0.902	1
24								0.583	0.642	0.699	0.755	0.811	0.865	[illegible]

Log V = 1.26405 -2.20809 (log D) +0.58980 (log D)(log H)
S.D. of coeff. 0.135923 0.061561
S.E. = [illegible]

Mean error = [illegible] percent
Ave. error = [illegible] percent
Std. deviation = 1[illegible] percent

Table 6.--*Top cubic volume, inside bark (6-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													*No. trees*
7			2.716	3.236	3.706	4.141	4.548	4.933	5.299					1
8			2.187	2.637	3.048	3.432	3.794	4.138	4.467					7
9			1.806	2.201	2.566	2.908	3.233	3.543	3.842	4.130				15
10			1.523	1.873	2.199	2.507	2.802	3.084	3.357	3.621				20
11			1.304	1.618	1.913	2.193	2.461	2.720	2.971	3.216				12
12			1.132	1.416	1.684	1.940	2.187	2.426	2.658	2.885	3.107			23
13			0.994	1.252	1.498	1.734	1.962	2.183	2.399	2.611	2.818			17
14			0.882	1.118	1.344	1.562	1.774	1.980	2.182	2.381	2.575	2.767		20
15			0.788	1.006	1.215	1.417	1.615	1.808	1.998	2.184	2.368	2.549		24
16				0.911	1.105	1.294	1.479	1.661	1.840	2.015	2.189	2.360		25
17				0.830	1.011	1.189	1.363	1.534	1.702	1.869	2.033	2.196		21
18				0.760	0.930	1.097	1.261	1.422	1.582	1.740	1.897	2.052		13
19				0.700	0.859	1.017	1.171	1.325	1.476	1.627	1.776	1.924		12
20				0.647	0.797	0.946	1.093	1.238	1.383	1.526	1.668	1.810		12
21						0.883	1.023	1.161	1.299	1.436	1.572	1.708	1.843	4
22						0.827	0.960	1.092	1.224	1.355	1.486	1.616	1.746	2
23							0.904	1.030	1.156	1.282	1.407	1.533	1.658	1
24								0.974	1.095	1.216	1.336	1.457	1.577	0

Log V = 1.80585 -2.68641 (log D) +0.719723 (log D) (log H)
S.D. of coeff. 0.175437 0.0696747
S.E. = 0.07392

Mean error = 17.5 percent
Ave. bias = -1.9 percent
Ave. deviation = 13.6 percent

Table 7.--*Top cubic volume, inside bark (7-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - -	- - -	- - -	- - -	- - -	- - -	*Cubic feet*	- - -	- - -	- - -	- - -	- - -	- - -	*No. trees*
8			3.970	4.888	5.744	6.553	7.326	8.069	8.786					0
9			3.182	3.964	4.701	5.404	6.079	6.733	7.367	7.984				8
10			2.610	3.287	3.930	4.548	5.145	5.726	6.292	6.846				18
11			2.183	2.774	3.342	3.891	4.424	4.945	5.456	5.957				12
12			1.853	2.377	2.882	3.374	3.855	4.326	4.790	5.246	5.697			23
13			1.595	2.061	2.515	2.959	3.396	3.825	4.249	4.668	5.082			17
14			1.387	1.807	2.217	2.621	3.020	3.413	3.803	4.189	4.572	4.952		20
15			1.217	1.598	1.972	2.341	2.707	3.070	3.430	3.788	4.144	4.497		24
16				1.425	1.767	2.107	2.444	2.780	3.114	3.447	3.779	4.110		25
17				1.279	1.594	1.907	2.220	2.533	2.844	3.155	3.466	3.776		21
18				1.156	1.446	1.737	2.028	2.320	2.611	2.903	3.195	3.487		13
19				1.050	1.319	1.590	1.862	2.135	2.408	2.683	2.958	3.233		12
20				0.958	1.209	1.462	1.716	1.973	2.230	2.489	2.749	3.010		12
21						1.350	1.589	1.830	2.073	2.318	2.564	2.811	3.060	4
22						1.251	1.476	1.704	1.934	2.166	2.399	2.635	2.871	2
23						1.163	1.376	1.591	1.809	2.030	2.252	2.476	2.702	1
24						1.085	1.286	1.491	1.698	1.907	2.119	2.333	2.549	0

Log V = 2.29311 - 3.06128 log D, + 1.800789 (log D) (log H)
S.E. of coeff. 0.18492 0.074664
S.E. = 0.07433

Mean error = 17.4 percent
Ave. bias = 11.0 percent
Ave. deviation = 13.5 percent

Table 8.--*Top cubic volume, inside bark (8-inch top diameter)--ponderosa pine*

D.b.h. (inches)	Total height (feet)													Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	130	
	Cubic feet													*No. trees*
9			4.993	6.332	7.614	8.852	10.054	11.227	12.375	13.500				2
10			4.051	5.196	6.304	7.382	8.436	9.470	10.486	11.488				9
11			3.352	4.345	5.314	6.263	7.197	8.118	9.028	9.927				12
12			2.821	3.691	4.546	5.391	6.226	7.053	7.874	8.688	9.498			23
13			2.406	3.176	3.939	4.696	5.448	6.197	6.943	7.686	8.426			17
14			2.077	2.764	3.449	4.133	4.816	5.498	6.180	6.861	7.541	6.229		20
15			1.811	2.428	3.047	3.669	4.293	4.918	5.545	6.173	6.802	7.432		24
16				2.151	2.714	3.283	3.855	4.431	5.010	5.591	6.176	6.762		25
17				1.920	2.435	2.957	3.485	4.017	4.555	5.096	5.640	6.188		21
18				1.724	2.198	2.679	3.168	3.663	4.163	4.668	5.178	5.691		13
19				1.558	1.995	2.441	2.895	3.357	3.824	4.297	4.775	5.258		12
20				1.415	1.819	2.234	2.658	3.090	3.528	3.972	4.423	4.878		12
21					1.667	2.054	2.451	2.855	3.267	3.686	4.111	4.542	4.978	4
22						1.896	2.268	2.649	3.037	3.433	3.835	4.243	4.657	2
23							2.106	2.465	2.832	3.207	3.588	3.976	4.369	1
24								2.301	2.649	3.004	3.367	3.736	4.111	0

Log V = 2.59226	-3.26371 (log D)	+0.865846 (log D) (log H)
S.D. of coeff.	0.163612	0.0656584

S.E. = 0.06339

Mean error = 15.0 percent
Ave. bias = -1.3 percent
Ave. deviation = 11.5 percent

Table 9.--[illegible]

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													No. trees
2	0.03	0.05	0.07	0.09	0.10	0.12								21
3	0.07	0.12	0.16	0.20	0.23	0.27								22
4	0.12	0.21	0.28	0.35	0.42	0.48	0.55							38
5	0.18	0.32	0.44	0.55	0.66	0.76	0.86	0.96						25
6	0.26	0.45	0.63	0.80	0.96	1.11	1.26	1.40						12
7	0.34	0.61	0.85	1.09	1.31	1.52	1.73	1.93	2.13					12
8	0.44	0.79	1.11	1.42	1.71	2.00	2.28	2.55	2.82					13
9		0.99	1.41	1.80	2.18	2.55	2.91	3.26	3.60	3.91				15
10		1.22	1.73	2.22	2.70	3.16	3.61	4.05	4.49	4.92				20
11			2.09	2.69	3.27	3.84	4.40	4.94	5.48	6.01				12
12				3.21	3.91	4.59	5.26	5.92	6.57	7.21	7.84			23
13				3.77	4.60	5.41	6.20	6.99	7.76	8.53	9.28			17
14				4.37	5.34	6.29	7.23	8.15	9.06	9.96	10.85	11.73		20
15				5.02	6.15	7.25	8.33	9.41	10.46	11.51	12.55	13.58		24
16				5.72	7.01	8.27	9.52	10.75	11.97	13.18	14.38	15.56		25
17				6.46	7.92	9.37	10.79	12.20	13.59	14.97	16.33	17.69		21
18					8.90	10.55	12.14	13.73	15.31	16.87	18.42	19.96		13
19					9.93	11.76	13.57	15.36	17.14	18.90	20.65	22.38		12
20						13.07	15.09	17.09	19.07	21.04	23.00	24.94	26.88	12
21						14.41	16.69	18.91	21.12	23.31	25.49	27.66	29.81	4
22						15.88	18.57	20.85	23.27	25.70	28.11	30.51	[illegible]	2
23						17.40	20.13	[illegible]	25.55	28.21	30.87	33.52	36.16	[illegible]
24						18.98	21.98	24.95	27.91	30.84	[illegible]	[illegible]	39.57	[illegible]

[illegible]

[illegible]

Table 10.--*Double bark thickness for stem sections of specified diameter--ponderosa pine*

D.o.b. (inches)	D.o.b. (10ths of inches) 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	D.o.b. (inches)
	Inches										
2	0.16	0.17	0.18	0.19	0.21	0.22	0.23	0.24	0.25	0.26	2
3	0.28	0.29	0.30	0.31	0.32	0.33	0.35	0.36	0.37	0.38	3
4	0.39	0.40	0.42	0.43	0.44	0.45	0.46	0.47	0.49	0.50	4
5	0.51	0.52	0.53	0.54	0.56	0.57	0.58	0.59	0.60	0.61	5
6	0.63	0.64	0.65	0.66	0.67	0.68	0.70	0.71	0.72	0.73	6
7	0.74	0.75	0.77	0.78	0.79	0.80	0.81	0.82	0.84	0.85	7
8	0.86	0.87	0.88	0.89	0.91	0.92	0.93	0.94	0.95	0.96	8
9	0.98	0.99	1.00	1.01	1.02	1.03	1.05	1.06	1.07	1.08	9
10	1.09	1.10	1.12	1.13	1.14	1.15	1.16	1.18	1.19	1.20	10
11	1.21	1.22	1.23	1.25	1.26	1.27	1.28	1.29	1.30	1.32	11
12	1.33	1.34	1.35	1.36	1.37	1.39	1.40	1.41	1.42	1.43	12
13	1.44	1.46	1.47	1.48	1.49	1.50	1.51	1.53	1.54	1.55	13
14	1.56	1.57	1.58	1.60	1.61	1.62	1.63	1.64	1.65	1.67	14
15	1.68	1.69	1.70	1.71	1.72	1.74	1.75	1.76	1.77	1.78	15
16	1.79	1.81	1.82	1.83	1.84	1.85	1.86	1.88	1.89	1.90	16
17	1.91	1.92	1.93	1.95	1.96	1.97	1.98	1.99	2.00	2.02	17
18	2.03	2.04	2.05	2.06	2.07	2.09	2.10	2.11	2.12	2.13	18
19	2.14	2.16	2.17	2.18	2.19	2.20	2.22	2.23	2.24	2.25	19
20	2.26	2.27	2.29	2.30	2.31	2.32	2.33	2.34	2.36	2.37	20

Values computed from the single-bark-thickness equation:

T = -0.0376115 +0.0584243 (D.o.b.)
S.D. of coeff. 0.00044242
S.E. = 0.080279
R^2 = 0.906
N = 1,810

Table 11.--[illegible]

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	Cubic feet												No. trees
2	0.12	0.21	0.35	0.46	0.57	0.68	0.79						17
3	0.27	0.52	0.77	1.01	1.25	1.50	1.74						18
4		0.90	1.34	1.76	2.18	2.60	3.02	3.45					23
5		1.39	2.05	2.71	3.36	4.00	4.64	5.28					16
6		1.97	2.92	3.85	4.77	5.69	6.60	7.50					8
7			3.92	5.18	6.42	7.65	8.88	10.10	11.31	12.52			13
8			5.08	6.70	8.30	9.90	11.48	13.06	14.63	16.19			16
9			6.37	8.40	10.42	12.42	14.41	16.39	18.35	20.31	22.27		23
10			7.80	10.29	12.76	15.21	17.65	20.07	22.48	24.89	27.28		23
11				12.57	15.34	18.28	21.21	24.12	27.02	29.90	32.78		12
12					18.14	21.62	25.08	28.52	31.95	35.36	38.76		24
13					21.16	25.22	29.26	33.28	37.28	41.26	45.23		10
14					24.41	29.09	33.75	38.38	43.00	47.59	52.17		10
15					27.88	33.25	38.55	43.84	49.11	54.36	59.58		6
16					31.57	37.65	43.65	49.65	55.61	61.55	67.47	73.37	2
17					35.48	42.29	49.06	55.80	62.50	69.18	75.83	82.46	5
18					39.61	47.22	54.77	62.29	69.78	77.23	84.66	92.06	1
19					43.86	52.40	60.79	69.13	77.44	85.71	93.95	102.17	10
20						57.84	67.10	76.31	85.48	94.62	103.72	112.78	6

[illegible]

Table 12.--*Top cubic volume, inside bark (2-inch top diameter)--lodgepole pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	Cubic feet												*No. trees*
3	0.074	0.099	0.117	0.132	0.144	0.156	0.166						21
4		0.067	0.083	0.096	0.108	0.119	0.129	0.138					23
5		0.050	0.064	0.076	0.087	0.097	0.106	0.115					16
6		0.039	0.051	0.062	0.072	0.082	0.091	0.099					8
7			0.043	0.053	0.062	0.071	0.079	0.088	0.095	0.103			13
8			0.036	0.046	0.054	0.063	0.071	0.079	0.086	0.094			16
9			0.032	0.040	0.048	0.056	0.064	0.071	0.079	0.086	0.093		23
10			0.028	0.036	0.044	0.051	0.058	0.065	0.072	0.079	0.086		23
11				0.032	0.040	0.047	0.054	0.060	0.067	0.074	0.081		12
12					0.036	0.043	0.050	0.056	0.063	0.069	0.076		24
13					0.034	0.040	0.046	0.053	0.059	0.065	0.072		10
14					0.031	0.037	0.043	0.050	0.056	0.062	0.068		10
15					0.029	0.035	0.041	0.047	0.053	0.059	0.065		6
16					0.027	0.033	0.039	0.045	0.050	0.056	0.062	0.068	2
17						0.031	0.037	0.042	0.048	0.054	0.060	0.065	5
18						0.030	0.035	0.040	0.046	0.052	0.057	0.063	1
19						0.028	0.033	0.039	0.044	0.050	0.055	0.061	0
20						0.027	0.032	0.037	0.042	0.048	0.053	0.059	0

Log V = -0.365736 -2.46962 (log D) +0.86752 (log D) (log H)
S.D. of coeff. 0.248634 0.111916
S.E. = 0.08814

Mean error = 21.8 percent
Ave. bias = -3.07 percent
Ave. deviation = 16.7 percent

Table 13.--Top cubic volume, inside bark (8-inch top diameter)--lodgepole pine

D.b.h. (Inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	- - -	- - -	- - -	- - -	- - -	- - -	Cubic feet	- - -	- - -	- - -	- - -	- - -	No. trees
4		0.305	0.369	0.422	0.469	0.510	0.549	0.584					24
5		0.219	0.273	0.319	0.361	0.398	0.433	0.466					16
6		0.167	0.214	0.254	0.291	0.325	0.357	0.387					8
7			0.174	0.210	0.243	0.274	0.304	0.331	0.358	0.384			13
8			0.145	0.178	0.208	0.236	0.264	0.290	0.315	0.339			16
9			0.124	0.153	0.181	0.207	0.233	0.257	0.281	0.303	0.326		23
10			0.108	0.133	0.160	0.185	0.208	0.231	0.253	0.275	0.296		23
11				0.119	0.143	0.166	0.188	0.210	0.231	0.251	0.272		12
12					0.129	0.151	0.172	0.192	0.212	0.232	0.251		24
13					0.118	0.138	0.158	0.177	0.196	0.215	0.234		10
14					0.108	0.127	0.146	0.164	0.183	0.201	0.218		10
15					0.100	0.118	0.136	0.153	0.171	0.188	0.205		6
16					0.092	0.110	0.127	0.144	0.160	0.177	0.194	0.210	2
17						0.102	0.119	0.135	0.151	0.167	0.183	0.199	5
18						0.096	0.112	0.127	0.143	0.158	0.174	0.189	1
19						0.091	0.106	0.121	0.136	0.151	0.166	0.181	2
20						0.086	0.100	0.114	0.129	0.141	0.158	0.173	[illegible]

Log V = 0.57676 -2.49626 (log D) +0.772565 (log D) (log H)
S.D. of coeff. 0.22006 0.127401
S.E. = 0.09357

Mean error = [illegible] percent
Ave. Bias = [illegible] percent
Ave. Deviation = 17.5 percent

Table 14.--*Top cubic volume, inside bark (4-inch top diameter)--lodgepole pine*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
5		0.630	0.777	0.902	1.012	1.113	1.205	1.291					16
6		0.477	0.603	0.712	0.810	0.900	0.983	1.062					8
7			0.487	0.583	0.671	0.752	0.828	0.900	0.969	1.035			13
8			0.405	0.491	0.570	0.644	0.713	0.780	0.844	0.906			16
9			0.344	0.421	0.493	0.561	0.626	0.688	0.747	0.805	0.861		23
10			0.297	0.367	0.433	0.496	0.556	0.614	0.670	0.725	0.778		23
11				0.325	0.386	0.444	0.500	0.555	0.607	0.659	0.709		12
12					0.347	0.401	0.454	0.505	0.555	0.604	0.652		24
13					0.314	0.366	0.415	0.464	0.511	0.557	0.603		10
14					0.287	0.335	0.382	0.428	0.473	0.518	0.561		10
15					0.264	0.309	0.354	0.398	0.441	0.483	0.525		6
16					0.244	0.287	0.329	0.371	0.412	0.453	0.493	0.533	2
17						0.267	0.308	0.348	0.387	0.426	0.465	0.503	5
18						0.250	0.289	0.327	0.365	0.402	0.440	0.477	1
19						0.235	0.272	0.309	0.345	0.381	0.417	0.453	0
20						0.221	0.257	0.292	0.327	0.362	0.397	0.432	0

Log V = 0.860507 -2.48286 (log D) +0.741235 (log D) (log H)
S.D. of coeff. 0.295097 0.129431
S.E. = 0.08588

Mean error = 20.6 percent
Ave. bias = -2.69 percent
Ave. deviation = 15.5 percent

Table 15.--Dry cubic volume, inside bark (6-inch top diameter)--Lodgepole pine

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												No. trees
6		1.133	1.422	1.672	1.894	2.098	2.288	2.466					6
7			1.135	1.353	1.550	1.732	1.903	2.064	2.217	2.364			13
8			0.934	1.126	1.303	1.467	1.622	1.769	1.910	2.046			16
9			0.786	0.958	1.117	1.267	1.409	1.544	1.674	1.800	1.922		23
10			0.674	0.829	0.974	1.111	1.242	1.367	1.488	1.606	1.720		23
11				0.728	0.861	0.987	1.108	1.225	1.338	1.448	1.555		12
12					0.768	0.885	0.998	1.108	1.214	1.318	1.419		24
13					0.692	0.801	0.907	1.010	1.110	1.208	1.304		10
14					0.629	0.731	0.830	0.927	1.022	1.115	1.206		10
15					0.575	0.671	0.764	0.856	0.946	1.034	1.121		6
16					0.528	0.619	0.708	0.795	0.880	0.964	1.048	1.130	2
17						0.574	0.658	0.741	0.822	0.903	0.983	1.062	5
18						0.535	0.615	0.693	0.771	0.849	0.925	1.001	1
19						0.500	0.576	0.652	0.726	0.800	0.874	0.947	0
20						0.469	0.542	0.614	0.686	0.757	0.828	0.898	0

Log V = 1.29[illegible]8 2.32686 (log D) +0.720985 (log D) (log H)
S.E. of coeff. 0.286708 0.130059
S.E. = 0.07350

Mean error = 17.1 percent
Ave. bias = -1.7 percent
Std. deviation = 13.7 percent

Table 16.--*Top cubic volume, inside bark (6-inch top diameter)--lodgepole pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	Cubic feet												*No. trees*
7			2.337	2.845	3.315	3.756	4.174	4.574	4.958	5.329			11
8			1.844	2.275	2.679	3.061	3.427	3.779	4.119	4.449			16
9			1.495	1.868	2.220	2.556	2.880	3.193	3.498	3.794	4.085		23
10			1.241	1.566	1.877	2.176	2.465	2.747	3.022	3.291	3.555		23
11				1.335	1.612	1.880	2.141	2.397	2.647	2.893	3.136		12
12					1.403	1.646	1.883	2.116	2.346	2.573	2.796		24
13					1.235	1.456	1.673	1.888	2.099	2.309	2.516		10
14					1.097	1.300	1.500	1.698	1.894	2.089	2.282		10
15					0.983	1.170	1.355	1.538	1.721	1.903	2.084		6
16					0.887	1.060	1.231	1.403	1.574	1.744	1.914	2.084	2
17						0.966	1.126	1.286	1.447	1.607	1.767	1.927	5
18						0.885	1.035	1.185	1.336	1.487	1.639	1.791	1
19						0.814	0.955	1.097	1.240	1.383	1.526	1.670	0
20						0.753	0.886	1.020	1.154	1.290	1.426	1.564	0

Log V = 1.86838 -2.97158 (log D) +0.810267 (log D) (log H)
S.D. of coeff. 0.279111 0.127879
S.E. = 0.06773

Mean error = 16.0 percent
Ave. bias = -1.50 percent
Ave. deviation = 12.9 percent

Table 17.--Tree cubic volume, inside bark ([illegible]-inch top diameter)--[illegible] pine

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	Cubic feet												No. trees
8			3.195	4.083	4.958	5.768	6.578	7.371	8.149	8.915			17
9			2.568	3.249	3.972	4.681	5.378	6.065	6.744	7.415	8.080		23
10			2.019	2.649	3.270	3.883	4.492	5.095	5.694	6.289	6.881		23
11				2.202	2.742	3.280	3.816	4.351	4.885	5.418	5.950		12
12					2.334	2.811	3.289	3.768	4.248	4.729	5.211		24
13					2.014	2.459	2.868	3.300	3.735	4.173	4.612		10
14					1.756	2.139	2.527	2.919	3.316	3.716	4.119		10
15					1.546	1.892	2.243	2.604	2.968	3.336	3.708		6
16					1.372	1.688	2.011	2.340	2.675	3.016	3.361	3.710	2
17						1.516	1.815	2.117	2.427	2.743	3.064	3.390	3
18						1.374	1.644	1.926	2.214	2.508	2.808	3.113	1
19						1.244	1.499	1.761	2.031	2.305	2.586	2.872	0
20						1.136	1.373	1.618	1.869	2.127	2.391	2.661	0

log V = 2.5[illegible] [illegible] (log D) +0.[illegible]3[illegible]81 (log D) (log H)
S.D. of coeff. 0.2[illegible]33 0.119[illegible]9[illegible]
S.E. = [illegible]

Mean error = 15.[illegible] percent
[illegible] = [illegible] percent
[illegible] = 1[illegible] percent

Table 18.--*Top cubic volume, inside bark (8-inch top diameter)--lodgepole pine*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
9			4.403	5.645	6.846	8.014	9.156	10.276	11.377	12.462	13.532		23
10			3.505	4.548	5.567	6.566	7.550	8.520	9.479	10.428	11.368		23
11				3.741	4.617	5.483	6.341	7.192	8.036	8.876	9.711		12
12					3.892	4.651	5.407	6.160	6.912	7.662	8.410		24
13					3.326	3.997	4.670	5.343	6.017	6.692	7.367		10
14					2.875	3.474	4.077	4.683	5.292	5.904	6.518		10
15					2.511	3.049	3.593	4.142	4.696	5.254	5.815		6
16						2.699	3.193	3.693	4.199	4.710	5.226	5.747	2
17						2.406	2.857	3.316	3.781	4.252	4.728	5.209	5
18						2.160	2.573	2.995	3.424	3.860	4.302	4.749	1
19						1.950	2.331	2.720	3.118	3.523	3.934	4.351	0
20						1.769	2.122	2.483	2.853	3.230	3.614	4.004	0

Log V = 2.70909 -3.50204 (log D) +0.905578 (log D) (log H)
S.D. of coeff. 0.282546 0.130545
S.E. = 0.06436

Mean error = 14.8 percent
Ave. bias = -1.06 percent
Ave. deviation = 11.6 percent

Table 19.--*Gross cubic bark volume, entire stem--lodgepole pine*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	- - - - - -	- - - - - -	- - - - - -	- - - - - -	- - - - - -	- - - - - -	*Cubic feet*	- - - - - -	- - - - - -	- - - - - -	- - - - - -	- - - - - -	*No. trees*
2	0.02	0.04	0.06	0.07	0.09	0.11							17
3	0.03	0.06	0.10	0.13	0.16	0.19	0.23	0.27					18
4	0.04	0.09	0.14	0.19	0.24	0.29	0.35	0.41					23
5	0.05	0.12	0.19	0.26	0.34	0.41	0.48	0.58					16
6	0.05	0.16	0.25	0.34	0.44	0.53	0.63	0.76					8
7			0.30	0.42	0.54	0.67	0.80	0.93	1.06	1.29			13
8			0.37	0.51	0.66	0.82	0.98	1.14	1.30	1.59			16
9			0.43	0.60	0.78	0.97	1.16	1.36	1.56	1.77	2.20		23
10			0.49	0.70	0.91	1.13	1.36	1.60	1.84	2.08	2.61		23
11					1.04	1.30	1.57	1.84	2.13	2.42	3.04		12
12					1.18	1.48	1.79	2.11	2.45	2.77	3.11		24
13					1.33	1.67	2.02	2.38	2.75	3.13	3.52		10
14					1.48	1.86	2.25	2.66	3.08	3.51	3.96		10
15					1.63	2.06	2.50	2.95	3.42	3.91	4.41		6
16						2.26	2.75	3.26	3.78	4.32	4.88	5.45	2
17						2.47	3.01	3.57	4.15	4.75	5.36	6.00	3
18						2.69	3.28	3.89	4.53	5.19	5.87	6.56	1
19						2.91	3.55	4.23	4.92	5.64	6.39	7.15	0
20						3.14	3.84	4.57	5.33	6.11	6.92	7.75	0

Log V = [illegible] +0.817022 (log D) +0.820817 (log H) +0.367366 (log D) (log H)
S.E. of coeff [illegible] [illegible] 0.111035
S.E. = [illegible]

[illegible]
[illegible]
[illegible]

Table 20.--*Double bark thickness for stem sections of specified diameter--lodgepole pine*

D.o.b. (inches)	D.o.b. (10ths of inches)										D.o.b. (inches)
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
	Inches										
2	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	2
3	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.17	3
4	0.17	0.17	0.17	0.18	0.18	0.18	0.19	0.19	0.19	0.19	4
5	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.22	0.22	0.22	5
6	0.23	0.23	0.23	0.23	0.24	0.24	0.24	0.25	0.25	0.25	6
7	0.25	0.26	0.26	0.26	0.27	0.27	0.27	0.27	0.28	0.28	7
8	0.28	0.29	0.29	0.29	0.29	0.30	0.30	0.30	0.31	0.31	8
9	0.31	0.31	0.32	0.32	0.32	0.33	0.33	0.33	0.33	0.34	9
10	0.34	0.34	0.35	0.35	0.35	0.35	0.36	0.36	0.36	0.37	10
11	0.37	0.37	0.37	0.38	0.38	0.38	0.39	0.39	0.39	0.39	11
12	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.42	0.42	0.42	12
13	0.43	0.43	0.43	0.43	0.44	0.44	0.44	0.45	0.45	0.45	13
14	0.45	0.46	0.46	0.46	0.47	0.47	0.47	0.47	0.48	0.48	14
15	0.48	0.49	0.49	0.49	0.49	0.50	0.50	0.50	0.51	0.51	15
16	0.51	0.51	0.52	0.52	0.52	0.53	0.53	0.53	0.53	0.54	16
17	0.54	0.54	0.55	0.55	0.55	0.55	0.56	0.56	0.56	0.57	17
18	0.57	0.57	0.57	0.58	0.58	0.58	0.59	0.59	0.59	0.59	18

Values computed from the single-bark-thickness equation:

T = 0.0271161 + 0.0142837 (D.o.b.)
S.D. of coeff. 0.000378354
S.E. = 0.0402561
R^2 = 0.556
N = 1,135

Table 21.--*Total cubic volume, inside bark, including stump and top--*[illegible]

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	*Cubic feet*	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	*No. trees*
2	0.11	0.21	0.30	0.40	0.49	0.59								17
3	0.23	0.45	0.66	0.86	1.06	1.27								20
4	0.40	0.77	1.13	1.49	1.84	2.18	2.53							18
5		1.18	1.73	2.27	2.80	3.33	3.86	4.38						26
6		1.66	2.44	3.21	3.96	4.71	5.45	6.15						17
7			3.27	4.29	5.31	6.31	7.30	8.29	9.26	10.24				16
8			4.21	5.53	6.83	8.12	9.40	10.67	11.93	13.19				14
9			5.26	6.92	8.51	10.16	11.76	13.34	14.92	16.49	18.05			15
10				8.43	10.44	12.40	14.36	16.30	18.22	20.13	22.04	23.93		18
11				10.12	12.50	14.86	17.20	19.52	21.83	24.12	26.41	28.68		29
12				11.93	14.75	17.53	20.22	23.03	25.75	28.45	31.11	33.82		23
13				13.89	17.16	20.40	23.61	[illegible]	29.97	33.12	36.25	39.37	42.47	23
14				15.90	19.77	23.48	27.18	[illegible]	34.49	38.11	41.72	45.31	[illegible]	[illegible]
15					22.51	26.76	30.98	35.16	39.31	43.44	47.55	51.64	55.71	7
16					25.45	30.25	35.01	39.73	44.43	49.10	[illegible]	[illegible]	62.97	4
17							39.27	44.58	49.84	55.08	60.29	[illegible]	70.64	3
18							44.77	[illegible]	[illegible]	61.39	67.16	[illegible]	78.73	1
19							[illegible]	55.04	61.35	68.01	74.15	80.85	[illegible]	1
20								[illegible]	67.84	74.96	82.05	89.13	[illegible]	2
21								[illegible]	[illegible]	82.27	[illegible]	97.75	105.40	[illegible]
22								[illegible]	81.28	90.82	[illegible]	[illegible]	[illegible]	[illegible]
23								[illegible]	88.42	97.72	[illegible]	[illegible]	[illegible]	[illegible]
24								[illegible]	[illegible]	107.23	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Table 22.--Top cubic volume, inside bark (2-inch top) [illegible]--western larch

D.b.h. (inches)	Total height (feet)													Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	130	
	Cubic feet													No. trees
3	0.092	0.124	0.147	0.166	0.183	0.198								20
4	0.056	0.081	0.102	0.119	0.134	0.148	0.161							18
5		0.059	0.076	0.091	0.105	0.118	0.130	0.141						26
6		0.045	0.060	0.074	0.086	0.098	0.109	0.120						17
7			0.049	0.062	0.073	0.084	0.094	0.104	0.144	0.124				16
8			0.042	0.053	0.063	0.073	0.083	0.092	0.102	0.111				14
9				0.046	0.055	0.065	0.074	0.083	0.092	0.101	0.109			18
10				0.040	0.049	0.058	0.067	0.076	0.084	0.092	0.101	0.109		18
11				0.036	0.045	0.053	0.061	0.069	0.077	0.085	0.093	0.101		20
12				0.033	0.041	0.048	0.056	0.064	0.072	0.080	0.087	0.095		23
13				0.030	0.037	0.045	0.052	0.060	0.067	0.075	0.082	0.090	0.097	23
14				0.027	0.034	0.041	0.049	0.056	0.063	0.070	0.077	0.085	0.092	10
15					0.032	0.039	0.045	0.052	0.059	0.066	0.073	0.080	0.088	7
16					0.030	0.036	0.043	0.049	0.056	0.063	0.070	0.077	0.084	4
17							0.040	0.047	0.053	0.060	0.067	0.073	0.080	3
18							0.038	0.044	0.051	0.057	0.064	0.070	0.077	1
19							0.036	0.042	0.048	0.055	0.061	0.067	0.074	1
20								0.040	0.046	0.052	0.059	0.065	0.071	2
21								0.039	0.044	0.050	0.056	0.063	0.069	1
22								0.037	0.043	0.049	0.054	0.060	0.067	0
23								0.036	0.041	0.047	0.053	0.059	0.065	0
24								0.034	0.040	0.045	0.051	0.057	0.063	0

Log V = -0.218386 -2.61784 (log D) +0.900808 (log D) (log H)
S.D. of coeff. 0.19533 0.08398
S.E. = 0.06500

Mean Error = 15.0 percent
Ave. Bias = -1.25 percent
Ave. Deviation = 12.1 percent

Table 23.--[illegible]

D.b.h. (inches)	Total height (feet)													Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	130	
	Cubic feet													No. trees
4	0.220	0.336	0.429	0.511	0.585	0.653	0.717							16
5		0.227	0.303	0.371	0.434	0.495	0.550	0.604						26
6		0.166	0.227	0.285	0.339	0.392	0.412	0.491						17
7			0.179	0.228	0.276	0.322	0.368	0.412	0.455	0.498				16
8			0.145	0.188	0.231	0.272	0.313	0.354	0.394	0.434				14
9				0.159	0.197	0.235	0.272	0.310	0.347	0.384	0.420			18
10				0.137	0.171	0.206	0.240	0.275	0.309	0.344	0.379	0.413		18
11				0.119	0.151	0.182	0.214	0.246	0.279	0.311	0.344	0.377		20
12				0.105	0.134	0.163	0.193	0.223	0.254	0.285	0.316	0.347		23
13				0.094	0.120	0.148	0.175	0.204	0.233	0.262	0.291	0.321	0.352	23
14				0.084	0.109	0.134	0.161	0.187	0.215	0.242	0.271	0.299	0.328	17
15					0.099	0.125	0.148	0.173	0.199	0.226	0.253	0.280	0.308	7
16					0.091	0.114	0.137	0.161	0.186	0.211	0.237	0.263	0.290	4
17							0.127	0.150	0.174	0.198	0.223	0.248	0.274	3
18							0.119	0.141	0.163	0.187	0.211	0.235	0.262	1
19							0.112	0.132	0.154	0.177	0.200	0.223	0.247	1
20								0.125	0.146	0.167	0.190	0.213	0.236	2
21								0.118	0.138	0.159	0.181	0.203	0.226	[illegible]
22								0.112	0.131	0.152	0.173	0.194	0.216	[illegible]
23								0.107	0.125	0.145	0.165	0.186	0.207	[illegible]
24								0.102	0.120	0.139	0.158	0.178	0.198	[illegible]

[illegible]

Table 24.--*Top cubic volume, inside bark (4-inch top diameter)--western larch*

D.b.h. (inches)	Total height (feet)													Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	130	
	Cubic feet													*No. trees*
5		0.668	0.902	1.117	1.318	1.508	1.691	1.867						18
6		0.466	0.651	0.826	0.993	1.154	1.311	1.464						17
7			0.494	0.640	0.782	0.921	1.057	1.192	1.325	1.456				16
8			0.389	0.513	0.635	0.757	0.877	0.997	1.116	1.235				14
9				0.422	0.529	0.637	0.744	0.852	0.960	1.068	1.177			18
10				0.355	0.450	0.546	0.643	0.740	0.839	0.938	1.038	1.139		18
11				0.303	0.388	0.474	0.562	0.652	0.743	0.834	0.927	1.021		20
12				0.262	0.339	0.417	0.498	0.580	0.664	0.750	0.836	0.924		23
13				0.230	0.299	0.371	0.445	0.522	0.600	0.679	0.760	0.843	0.926	23
14				0.203	0.267	0.333	0.402	0.473	0.545	0.620	0.696	0.774	0.853	10
15					0.240	0.301	0.365	0.431	0.499	0.569	0.641	0.715	0.790	7
16					0.217	0.274	0.333	0.395	0.460	0.526	0.594	0.664	0.735	4
17							0.306	0.365	0.425	0.488	0.553	0.619	0.688	3
18							0.283	0.338	0.395	0.455	0.516	0.580	0.645	1
19							0.262	0.314	0.369	0.426	0.484	0.545	0.608	1
20								0.294	0.345	0.399	0.456	0.514	0.574	2
21								0.275	0.324	0.376	0.430	0.486	0.544	1
22								0.258	0.306	0.355	0.407	0.461	0.516	0
23								0.244	0.289	0.336	0.386	0.438	0.491	0
24								0.230	0.273	0.319	0.367	0.417	0.469	0

Log V = 1.20417 -3.35498 (log D) +1.06157 (log D) (log H)
S.D. of coeff. 0.242998 0.100253
S.E. = 0.06686

Mean Error = 15.0 percent
Ave. Bias = -1.25 percent
Ave. Deviation = 11.6 percent

Table 25.--Top cubic volume, inside bark (6-inch top diameter)--western larch

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - -	- - -	- - -	- - -	- - -	- - -	Cubic feet	- - -	- - -	- - -	- - -	- - -	- - -	No. trees
6		1.183	1.633	2.053	2.452	2.835	3.205	3.565						7
7			1.212	1.555	1.886	2.207	2.522	2.831	3.134	3.433				16
8			0.937	1.222	1.502	1.777	2.049	2.318	2.584	2.848				14
9				0.988	1.228	1.468	1.706	1.943	2.180	2.416	2.652			18
10				0.817	1.026	1.237	1.448	1.660	1.872	2.085	2.299	2.513		18
11				0.688	0.872	1.059	1.248	1.439	1.632	1.825	2.020	2.217		20
12				0.588	0.752	0.920	1.090	1.264	1.439	1.616	1.796	1.977		25
13				0.509	0.656	0.808	0.963	1.121	1.282	1.445	1.611	1.779	1.949	23
14				0.445	0.578	0.716	0.858	1.003	1.152	1.303	1.457	1.614	1.772	13
15					0.511	0.640	0.771	0.905	1.043	1.183	1.327	1.474	1.623	7
16					0.464	0.576	0.697	0.821	0.950	1.081	1.216	1.354	1.494	4
17							0.634	0.750	0.870	0.994	1.120	1.250	1.382	3
18							0.580	0.689	0.801	0.917	1.037	1.159	1.284	1
19							0.535	0.633	0.741	0.851	0.963	1.080	1.199	1
20								0.588	0.688	0.792	0.899	1.009	1.123	2
21								0.547	0.641	0.740	0.841	0.946	1.055	1
22								0.510	0.600	0.693	0.790	0.890	0.991	[illegible]
23								0.477	0.566	0.651	0.744	0.840	0.939	[illegible]
24								0.448	0.535	0.614	0.702	0.794	0.888	[illegible]

Log V = 1.[illegible]6[illegible] [illegible] log D [illegible] -1.02285 [illegible] log H
S.E. of coeff. [illegible]5 [illegible]
S.E. = 0.0[illegible]5

Mean [illegible] [illegible] percent
[illegible] [illegible] percent
[illegible] [illegible] percent

Table 26.--*Top cubic volume, inside bark (6-inch top diameter)--western larch*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
							Cubic feet							*No. trees*
7			2.576	3.252	3.896	4.516	5.116	5.700	6.271	6.829				5
8			1.968	2.524	3.062	3.585	4.097	4.599	5.092	5.578				13
9				2.019	2.476	2.925	3.368	3.805	4.238	4.666	5.091			18
10				1.653	2.047	2.438	2.826	3.212	3.596	3.978	4.358	4.737		18
11				1.380	1.724	2.068	2.412	2.755	3.099	3.443	3.780	4.130		20
12				1.170	1.474	1.779	2.087	2.396	2.706	3.017	3.330	3.643		23
13				1.005	1.275	1.549	1.826	2.106	2.388	2.673	2.959	3.247	3.536	23
14				0.873	1.116	1.363	1.615	1.870	2.128	2.389	2.652	2.918	3.186	10
15					0.985	1.210	1.439	1.673	1.911	2.152	2.396	2.642	2.892	7
16					0.877	1.082	1.293	1.508	1.728	1.951	2.178	2.408	2.641	4
17							1.169	1.368	1.572	1.780	1.992	2.207	2.425	3
18							1.063	1.248	1.438	1.632	1.830	2.032	2.238	1
19							0.971	1.144	1.322	1.504	1.690	1.880	2.074	1
20								1.053	1.220	1.391	1.567	1.746	1.930	2
21								0.974	1.131	1.292	1.458	1.628	1.802	1
22								0.904	1.052	1.204	1.361	1.522	1.688	0
23								0.841	0.981	1.126	1.275	1.428	1.585	0
24								0.786	0.918	1.055	1.197	1.343	1.493	0

Log V = 2.11511 -3.43175 (log D) +0.958133 (log D) (log H)
S.D. of coeff. 0.256364 0.104981
S.E. = 0.06269

Mean Error = 14.1 percent
Ave. Bias = -1.21 percent
Ave. Deviation = 11.0 percent

Table 27.--[illegible] volume, inside bark 7-inch top diameter--western larch

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	Cubic feet	- - - -	- - - -	- - - -	- - - -	- - - -	Number
8			3.525	4.586	5.625	6.646	7.652	8.647	9.631	10.605				2
9				3.602	4.470	5.331	6.188	7.040	7.890	8.736	9.579			18
10				2.903	3.659	4.377	5.117	5.858	6.601	7.344	8.089	8.834		18
11				2.387	3.021	3.662	4.309	4.961	5.617	6.278	6.942	7.609		20
12				1.997	2.549	3.112	3.683	4.262	4.848	5.440	6.037	6.640		23
13				1.695	2.181	2.679	3.188	3.706	4.233	4.768	5.309	5.857	6.411	23
14				1.456	1.887	2.332	2.789	3.257	3.734	4.220	4.714	5.215	5.723	10
15					1.649	2.050	2.463	2.888	3.323	3.767	4.220	4.681	5.150	7
16					1.454	1.816	2.192	2.580	2.979	3.387	3.805	4.231	4.665	4
17							1.965	2.321	2.688	3.065	3.452	3.848	4.252	5
18							1.773	2.101	2.440	2.790	3.150	3.518	3.895	1
19							1.608	1.912	2.227	2.552	2.888	3.233	3.586	1
20								1.748	2.042	2.346	2.660	2.983	3.315	2
21								1.605	1.880	2.165	2.459	2.764	3.077	1
22								1.480	1.737	2.005	2.283	2.569	2.865	0
23								1.370	1.611	1.864	2.125	2.396	2.67[illegible]	0
24								1.272	1.499	1.737	1.985	2.242	2.507	0

log V = [illegible] 1.[illegible]7.88 (log D) + 1.01315 (log D) (log H)
S.E. of coeff. [illegible] 0.1[illegible]819
S.E. = 0.0[illegible]

[illegible] = [illegible] percent
[illegible] = [illegible] percent
[illegible] = [illegible] percent

Table 28.--*Top cubic volume, inside bark (8-inch top diameter)--western larch*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Cubic feet													*No. trees*
9				5.854	7.429	9.026	10.641	12.272	13.917	15.574	17.243			6
10				4.628	5.940	7.285	8.657	10.052	11.468	12.904	14.356	15.824		14
11				3.741	4.855	6.001	7.182	8.392	9.627	10.884	12.163	13.461		20
12				3.081	4.034	5.028	6.057	7.117	8.205	9.318	10.455	11.614		23
13				2.577	3.404	4.273	5.178	6.116	7.083	8.077	9.096	10.139	11.203	23
14				2.185	2.909	3.675	4.478	5.315	6.182	7.076	7.996	8.941	9.907	10
15					2.512	3.194	3.912	4.664	5.446	6.256	7.092	7.953	8.836	7
16					2.191	2.801	3.448	4.127	4.837	5.575	6.339	7.128	7.940	4
17							3.062	3.680	4.328	5.003	5.705	6.431	7.181	3
18							2.737	3.302	3.896	4.518	5.165	5.837	6.531	1
19							2.462	2.981	3.528	4.102	4.702	5.325	5.971	1
20								2.705	3.211	3.743	4.300	4.881	5.485	2
21								2.466	2.936	3.431	3.951	4.493	5.058	1
22								2.258	2.695	3.157	3.643	4.152	4.683	0
23								2.076	2.484	2.917	3.372	3.851	4.350	0
24								1.915	2.297	2.703	3.132	3.582	4.054	0

Log V = 2.89616 -4.02373 (log D) +1.11914 (log D) (log H)
S.D. of coeff. 0.302677 0.120186
S.E. = 0.06567

Mean Error = 15.1 percent
Ave. Bias = -1.14 percent
Ave. Deviation = 11.4 percent

Table 29.--Gross cubic bark volume, entire stem--western larch

D.b.h. (inches)	10	20	30	40	50	60	70	80	90	100	110	120	130	Sample size
	Total height (feet)													
	Cubic feet													No. trees
2	0.02	0.04	0.07	0.09	0.11	0.13								17
3	0.05	0.10	0.15	0.20	0.25	0.30								20
4	0.09	0.17	0.26	0.35	0.44	0.53	0.62							18
5		0.27	0.41	0.55	0.69	0.83	0.98	1.12						16
6		0.39	0.60	0.80	1.00	1.20	1.41	1.61						17
7			0.81	1.09	1.36	1.64	1.92	2.20	2.47	2.75				16
8			1.06	1.42	1.78	2.14	2.51	2.87	3.24	3.60				14
9				1.80	2.26	2.72	3.18	3.64	4.10	4.56	5.03			18
10				2.22	2.79	3.36	3.92	4.49	5.07	5.64	6.21	6.78		18
11				2.69	3.38	4.06	4.75	5.44	6.13	6.83	7.52	8.21		20
12				3.21	4.02	4.84	5.66	6.48	7.31	8.13	8.96	9.78		23
13				3.77	4.72	5.69	6.65	7.61	8.58	9.55	10.52	11.49	12.46	25
14				4.37	5.48	6.60	7.72	8.84	9.96	11.08	12.21	13.33	14.46	10
15					6.30	7.58	8.86	10.15	11.44	12.73	14.02	15.32	16.61	7
16						8.63	10.09	11.55	13.02	14.49	15.96	17.44	18.91	4
17						9.75	11.40	13.05	14.71	16.37	18.03	19.69	21.36	[illegible]
18						10.95	12.78	14.64	16.50	18.36	20.22	22.09	23.96	1
19							14.25	16.32	18.39	20.46	22.54	24.62	26.71	1
20							15.79	18.09	20.38	22.68	24.99	27.30	[illegible]	2
21							17.41	19.95	22.48	25.02	27.56	30.11	[illegible]	1
22							19.11	[illegible]	24.69	27.47	30.26	[illegible].06	[illegible]	0
23							20.90	23.95	26.99	30.04	[illegible]	[illegible].14	[illegible]	0
24							22.79	26.09	29.40	[illegible]	[illegible]	39.37	[illegible]	0

[illegible] 3.2[illegible] +2.0081 (log D) +1.0104 (log H)
[illegible] 0.04317 0.00[illegible]
S.E. [illegible] 0.0[illegible]

Mean [illegible] = [illegible] percent
[illegible] = [illegible] percent
[illegible] deviation = [illegible] percent

Table 30.--*Double bark thickness for stem sections of specified diameter--western larch*

D.o.b. (inches)	D.o.b. (10ths of inches) 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	D.o.b. (inches)
	- - - -	- - - -	- - - -	- - - -	*Inches*	- - - -	- - - -	- - - -	- - - -	- - - -	
2	0.16	0.17	0.18	0.19	0.21	0.22	0.23	0.24	0.26	0.27	2
3	0.28	0.29	0.31	0.32	0.33	0.35	0.36	0.37	0.38	0.40	3
4	0.41	0.42	0.43	0.45	0.46	0.47	0.48	0.50	0.51	0.52	4
5	0.53	0.55	0.56	0.57	0.58	0.60	0.61	0.62	0.63	0.65	5
6	0.66	0.67	0.68	0.70	0.71	0.72	0.73	0.75	0.76	0.77	6
7	0.79	0.80	0.81	0.82	0.84	0.85	0.86	0.87	0.89	0.90	7
8	0.91	0.92	0.94	0.95	0.96	0.97	0.99	1.00	1.01	1.02	8
9	1.04	1.05	1.06	1.07	1.09	1.10	1.11	1.12	1.14	1.15	9
10	1.16	1.17	1.19	1.20	1.21	1.23	1.24	1.25	1.26	1.28	10
11	1.29	1.30	1.31	1.33	1.34	1.35	1.36	1.38	1.39	1.40	11
12	1.41	1.43	1.44	1.45	1.46	1.48	1.49	1.50	1.51	1.53	12
13	1.54	1.55	1.56	1.58	1.59	1.60	1.61	1.63	1.64	1.65	13
14	1.67	1.68	1.69	1.70	1.72	1.73	1.74	1.75	1.77	1.78	14
15	1.79	1.80	1.82	1.83	1.84	1.85	1.87	1.88	1.89	1.90	15
16	1.92	1.93	1.94	1.95	1.97	1.98	1.99	2.00	2.02	2.03	16
17	2.04	2.05	2.07	2.08	2.09	2.11	2.12	2.13	2.14	2.16	17
18	2.17	2.18	2.19	2.21	2.22	2.23	2.24	2.26	2.27	2.28	18
19	2.29	2.31	2.32	2.33	2.34	2.36	2.37	2.38	2.39	2.41	19
20	2.42	2.43	2.44	2.46	2.47	2.48	2.49	2.51	2.52	2.53	20

Values computed from the single-bark-thickness equation:

T = -0.0474573 +0.0628597 (D.o.b.)
S.D. of coeff. 0.00056604
S.E. = 0.068016
R^2 = 0.905
N = 1,295

Table 31.--*Total cubic volume, inside bark, including stump and top--Douglas-fir*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
2	0.19	0.25	0.33	0.43	0.57	0.76							27
3	0.44	0.56	0.72	0.93	1.20	1.55							32
4	0.79	1.00	1.27	1.61	2.04	2.59	3.29						22
5		1.56	1.96	2.45	3.07	3.85	4.82						26
6		2.25	2.79	3.46	4.30	5.33	6.60	8.18	10.15				16
7		3.07	3.77	4.64	5.70	7.00	8.61	10.58	13.00				24
8		4.01	4.89	5.97	7.28	8.88	10.83	13.22	16.12				15
9		5.08	6.15	7.46	9.01	10.95	13.27	16.08	19.48				19
10			7.56	9.10	10.96	13.21	15.91	19.16	23.08				12
11			9.10	10.90	13.06	15.65	18.74	22.46	26.91	32.24			18
12			10.78	12.85	15.32	18.26	21.77	25.96	30.95	36.90	44.00		26
13			12.59	14.95	17.74	21.06	24.99	29.66	35.21	41.79	49.59		18
14				17.19	20.32	24.02	28.39	33.56	39.66	46.88	55.41		13
15				19.59	23.07	27.16	31.97	37.64	44.32	52.18	61.43		12
16				22.13	25.96	30.46	35.75	41.91	49.17	57.68	67.66		18
17				24.82	29.02	33.92	39.66	46.37	54.21	63.37	74.09		21
18				27.65	32.23	37.55	43.76	51.00	59.43	69.25	80.70		13
19					35.59	41.31	48.03	55.80	64.83	75.32	87.50	101.66	11
20						45.29	52.47	60.78	70.41	81.56	94.48	109.45	8
21						49.39	57.06	65.92	76.15	87.98	101.63	117.41	3
22						53.05	61.82	71.23	82.07	94.57	108.96	125.54	4
23						58.07	66.74	76.70	88.16	101.32	116.45	133.84	[illegible]
24						62.63	71.81	82.34	94.40	108.24	124.11	142.59	[illegible]
25							77.04	88.13	100.81	115.32	132.92	153.91	2
26							82.42	91.08	107.38	[illegible]	139.46	[illegible]	1

Log V = -2.48077 +2.11411 (log D) +0.0137202 (H) -0.00563672 (log D)(H)
S.D. of coeff. 0.0[illegible]75[illegible] 0.000[illegible]52[illegible] 0.000120823
S.E. = 0.04546

Mean error = 11.1 percent
Ave. bias = -0.85 percent
Ave. deviation = [illegible].9 percent

Table 32.--*Top cubic volume, inside bark (2-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	*Cubic feet*	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	*No. trees*
3	0.074	0.091	0.103	0.113	0.121	0.128							30
4	0.053	0.069	0.081	0.090	0.098	0.105	0.112						22
5		0.056	0.067	0.076	0.084	0.091	0.097						26
6		0.047	0.057	0.066	0.073	0.080	0.087	0.092	0.098				16
7		0.040	0.050	0.058	0.066	0.072	0.079	0.084	0.090				24
8		0.035	0.044	0.052	0.060	0.066	0.072	0.078	0.083				15
9		0.031	0.040	0.048	0.055	0.061	0.067	0.073	0.078				19
10			0.037	0.044	0.051	0.057	0.063	0.068	0.074				12
11			0.034	0.041	0.047	0.053	0.059	0.065	0.070				18
12			0.031	0.038	0.044	0.050	0.056	0.061	0.067	0.071			26
13			0.029	0.036	0.042	0.048	0.053	0.059	0.064	0.069	0.073		18
14				0.034	0.040	0.045	0.051	0.056	0.061	0.066	0.071		13
15				0.032	0.038	0.043	0.049	0.054	0.059	0.064	0.068		15
16				0.031	0.036	0.042	0.047	0.052	0.057	0.061	0.066		18
17				0.029	0.035	0.040	0.045	0.050	0.055	0.059	0.064		21
18				0.028	0.033	0.038	0.043	0.048	0.053	0.058	0.062		13
19					0.032	0.037	0.042	0.047	0.051	0.056	0.061	0.065	11
20					0.031	0.036	0.041	0.045	0.050	0.055	0.059	0.063	8
21						0.035	0.039	0.044	0.049	0.053	0.058	0.062	3
22						0.034	0.038	0.043	0.047	0.052	0.056	0.061	4
23						0.033	0.037	0.042	0.046	0.051	0.055	0.059	0
24						0.032	0.036	0.041	0.045	0.050	0.054	0.058	0
25							0.035	0.040	0.044	0.048	0.053	0.057	1
26							0.034	0.039	0.043	0.047	0.052	0.056	1

Log V = -0.57482	-1.79704 (log D)	+0.63400 (log D) (log H)
S.D. of coeff.	0.14463	0.064633
S.E. = 0.07169		

Mean error = 16.4 percent
Ave. bias = -1.5 percent
Ave. deviation = 12.6 percent

Table 33.--*Top cubic volume, inside bark (3-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
4	0.228	0.303	0.359	0.404	0.444	0.478	0.510						18
5		0.230	0.280	0.321	0.358	0.390	0.420						26
6		0.184	0.228	0.266	0.300	0.331	0.359	0.386	0.411				16
7		0.152	0.192	0.227	0.258	0.287	0.314	0.340	0.364				24
8		0.128	0.165	0.198	0.227	0.254	0.280	0.304	0.327				15
9		0.111	0.145	0.175	0.203	0.228	0.253	0.276	0.298				19
10			0.129	0.157	0.183	0.208	0.231	0.253	0.274				12
11			0.116	0.142	0.167	0.190	0.213	0.234	0.254				18
12			0.105	0.130	0.154	0.176	0.197	0.218	0.238	0.257	0.276		26
13			0.096	0.120	0.142	0.163	0.184	0.204	0.223	0.242	0.260		18
14				0.111	0.132	0.153	0.173	0.192	0.210	0.229	0.246		13
15				0.103	0.124	0.143	0.163	0.181	0.199	0.217	0.234		15
16				0.097	0.116	0.135	0.154	0.172	0.189	0.207	0.224		18
17				0.091	0.110	0.128	0.146	0.163	0.180	0.197	0.214		21
18				0.086	0.104	0.121	0.139	0.156	0.172	0.189	0.205		13
19					0.098	0.116	0.132	0.149	0.165	0.181	0.197	0.213	11
20					0.094	0.110	0.127	0.143	0.159	0.174	0.190	0.205	5
21						0.106	0.121	0.137	0.153	0.168	0.183	0.198	3
22						0.101	0.117	0.132	0.147	0.162	0.177	0.192	4
23						0.097	0.112	0.127	0.142	0.157	0.172	0.186	6
24						0.093	0.108	0.123	0.137	0.152	0.166	0.181	0
25							0.104	0.119	0.133	0.147	0.161	0.176	1
26							0.101	0.115	0.129	0.143	0.157	0.171	1

Log V = 0.22847 -2.13544 (log D) +0.68846 (log D)(log H)
S.D. of coeff. 0.14572 0.063693
S.E. = 0.06[illegible]

Mean error = 15.[illegible] percent
Agg. error = -4.70 percent
Ave. deviation = 11.8 percent

Table 34.--*Top cubic volume, inside bark (4-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
5		0.682	0.820	0.934	1.033	1.122	1.203						17
6		0.534	0.654	0.757	0.846	0.928	1.003	1.073	1.138				16
7		0.433	0.541	0.633	0.715	0.791	0.860	0.925	0.987				24
8		0.362	0.459	0.543	0.618	0.688	0.753	0.814	0.872				15
9		0.309	0.397	0.474	0.544	0.609	0.670	0.727	0.782				19
10			0.348	0.420	0.485	0.546	0.603	0.657	0.709				12
11			0.310	0.376	0.437	0.494	0.548	0.600	0.649				18
12			0.278	0.340	0.397	0.451	0.503	0.552	0.599	0.645	0.689		26
13			0.252	0.310	0.364	0.415	0.464	0.511	0.556	0.600	0.643		18
14				0.285	0.336	0.384	0.431	0.476	0.519	0.562	0.603		13
15				0.263	0.311	0.358	0.402	0.445	0.487	0.528	0.568		15
16				0.244	0.290	0.335	0.377	0.419	0.459	0.498	0.537		18
17				0.227	0.272	0.314	0.355	0.395	0.434	0.472	0.509		21
18				0.213	0.255	0.296	0.336	0.374	0.412	0.448	0.484		13
19					0.241	0.280	0.318	0.355	0.391	0.427	0.462	0.497	11
20					0.228	0.265	0.302	0.338	0.373	0.408	0.442	0.476	8
21						0.252	0.288	0.323	0.357	0.391	0.424	0.456	3
22						0.240	0.275	0.309	0.342	0.375	0.407	0.439	4
23						0.229	0.263	0.296	0.328	0.360	0.391	0.423	0
24						0.219	0.252	0.284	0.315	0.346	0.377	0.408	0
25							0.242	0.273	0.304	0.334	0.364	0.394	1
26							0.233	0.263	0.293	0.322	0.352	0.381	1

Log V = 0.77690 -2.19153 (log D) +0.64755 (log D) (log H)
S.D. of coeff. 0.141294 0.0606155
S.E. = 0.06072

Mean error = 14.3 percent
Ave. bias = -1.3 percent
Ave. deviation = 11.3 percent

Table 35.--*Top cubic volume, inside bark (4-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												*No. trees*
6		1.264	1.558	1.806	2.206	2.225	2.409	2.580	2.742				8
7		1.001	1.256	1.475	1.671	1.850	2.016	2.173	2.321				24
8		0.818	1.042	1.237	1.414	1.576	1.729	1.872	2.009				15
9		0.684	0.884	1.060	1.220	1.369	1.509	1.642	1.768				19
10			0.763	0.923	1.070	1.207	1.336	1.460	1.578				12
11			0.668	0.814	0.949	1.076	1.197	1.312	1.423				18
12			0.591	0.726	0.852	0.970	1.085	1.191	1.295	1.397			26
13			0.529	0.654	0.770	0.881	0.987	1.089	1.188	1.284	1.377		18
14				0.593	0.702	0.806	0.906	1.003	1.096	1.188	1.277		13
15				0.542	0.644	0.742	0.857	0.929	1.018	1.105	1.190		15
16				0.497	0.594	0.687	0.777	0.864	0.949	1.032	1.113		18
17				0.459	0.551	0.639	0.724	0.808	0.889	0.968	1.046		21
18				0.426	0.515	0.597	0.678	0.758	0.836	0.912	0.987		13
19					0.479	0.559	0.637	0.715	0.788	0.861	0.934	1.005	11
20					0.450	0.526	0.601	0.674	0.746	0.816	0.886	0.955	8
21						0.496	0.568	0.638	0.707	0.775	0.845	0.910	5
22						0.469	0.538	0.606	0.672	0.738	0.804	0.868	4
23						0.445	0.511	0.576	0.641	0.705	0.768	0.830	[illegible]
24						0.425	0.487	0.550	0.612	0.674	0.735	0.796	1
25							0.464	0.525	0.586	0.646	0.705	0.764	1
26							0.444	0.503	0.561	0.619	0.677	0.735	1

Log V = 1.25870 −2.37425 (log D) +0.00145 (log D) (log H)
S.E. of coeff. 0.15684 0.00[illegible]
S.E. = 0.0[illegible]

Mean error = 15.6 percent
Ave. bias = −2.6 percent
Ave. deviation = 11.8 percent

Table 36.--Top cubic volume, inside bark (6-inch top diameter)--Douglas-fir

D.b.h. (inches)	Total height (feet)												Sample size
	10	20	30	40	50	60	70	80	90	100	110	120	
	Cubic feet												No. trees
7			2.447	2.904	3.317	3.698	4.054	4.389	4.709				7
8			1.992	2.392	2.758	3.097	3.417	3.720	4.010				15
9			1.662	2.016	2.343	2.649	2.938	3.214	3.480				19
10			1.413	1.730	2.025	2.303	2.567	2.821	3.065				12
11			1.220	1.507	1.775	2.029	2.272	2.506	2.733				18
12			1.067	1.328	1.574	1.808	2.033	2.250	2.461	2.667			26
13			0.943	1.182	1.409	1.626	1.835	2.038	2.235	2.428	2.617		18
14				1.062	1.271	1.473	1.660	1.859	2.044	2.226	2.404		13
15				0.960	1.156	1.344	1.528	1.706	1.881	2.053	2.222		15
16				0.875	1.057	1.234	1.406	1.575	1.741	1.904	2.064		18
17				0.801	0.972	1.138	1.301	1.461	1.618	1.773	1.926		21
18				0.737	0.898	1.055	1.209	1.361	1.511	1.658	1.804		13
19					0.833	0.982	1.129	1.273	1.416	1.557	1.696	1.835	11
20					0.776	0.917	1.057	1.195	1.331	1.466	1.600	1.733	8
21						0.860	0.993	1.124	1.255	1.384	1.513	1.641	3
22						0.808	0.935	1.061	1.187	1.311	1.435	1.558	4
23						0.762	0.884	1.004	1.125	1.244	1.364	1.483	0
24						0.720	0.837	0.953	1.069	1.184	1.299	1.414	0
25							0.794	0.906	1.017	1.129	1.240	1.351	1
26							0.755	0.863	0.970	1.078	1.186	1.293	1

Log V = 1.69009 -2.58148 (log D) +0.70505 (log D) (log H)
S.D. of coeff. 0.180394 0.0762105
S.E. = 0.07278

Mean error = 17.2 percent
Ave. bias = -1.9 percent
Ave. deviation = 13.4 percent

Table 37.--*Top cubic volume, inside bark (7-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
							Cubic feet						*No. trees*
8			3.534	4.253	4.910	5.522	6.098	6.645	7.169				1
9			2.916	3.547	4.128	4.673	5.190	5.683	6.157				16
10			2.456	3.015	3.535	4.025	4.493	4.941	5.374				12
11			2.102	2.603	3.071	3.517	3.943	4.354	4.752				18
12			1.824	2.276	2.702	3.109	3.500	3.879	4.247	4.605			26
13			1.600	2.011	2.401	2.775	3.137	3.488	3.830	4.164	4.491		18
14				1.794	2.153	2.499	2.834	3.161	3.480	3.793	4.100		13
15				1.613	1.945	2.266	2.579	2.884	3.183	3.477	3.767		15
16				1.460	1.768	2.068	2.361	2.647	2.929	3.206	3.479		18
17				1.330	1.617	1.898	2.173	2.443	2.708	2.971	3.230		21
18				1.218	1.487	1.750	2.009	2.264	2.516	2.764	3.010		13
19					1.373	1.621	1.866	2.107	2.346	2.582	2.817	3.049	11
20					1.273	1.507	1.739	1.968	2.196	2.421	2.645	2.867	8
21					1.185	1.407	1.627	1.845	2.062	2.277	2.491	2.704	3
22						1.317	1.526	1.734	1.941	2.147	2.352	2.557	4
23						1.237	1.436	1.635	1.883	2.030	2.227	2.424	0
24						1.164	1.355	1.545	1.735	1.925	2.114	2.303	0
25							1.281	1.464	1.646	1.828	2.010	2.192	1
26							1.214	1.389	1.565	1.740	1.916	2.091	1

log V = 2.02163 −2.68436 (log D) +0.71282 (log D) (log H)
S.E. of coeff. 0.180002 0.074193
S.E. = 0.06808

Mean error = 16.3 percent
Ave. bias = −1.6 percent
Ave. deviation = 12.4 percent

Table 38.--*Top cubic volume, inside bark (8-inch top diameter)--Douglas-fir*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	Cubic feet												*No. trees*
9			4.701	5.896	7.029	8.115	9.162	10.178	11.167				3
10			3.862	4.897	5.887	6.843	7.772	8.677	9.563				11
11			3.233	4.140	5.015	5.865	6.696	7.511	8.311				18
12			2.748	3.551	4.332	5.095	5.845	6.583	7.312	8.031			26
13			2.367	3.084	3.786	4.477	5.158	5.832	6.499	7.160	7.815		18
14				2.706	3.342	3.971	4.594	5.213	5.827	6.438	7.045		13
15				2.396	2.975	3.552	4.125	4.696	5.264	5.831	6.396		15
16				2.138	2.669	3.199	3.729	4.258	4.787	5.316	5.844		18
17				1.922	2.410	2.901	3.392	3.885	4.378	4.873	5.368		21
18				1.737	2.189	2.644	3.102	3.563	4.025	4.489	4.955		13
19					1.999	2.423	2.851	3.283	3.717	4.154	4.594	5.036	11
20					1.834	2.230	2.632	3.037	3.447	3.860	4.275	4.694	8
21					1.689	2.061	2.438	2.821	3.208	3.599	3.993	4.391	3
22						1.911	2.267	2.629	2.995	3.366	3.741	4.120	4
23						1.779	2.115	2.458	2.806	3.158	3.515	3.877	0
24						1.661	1.979	2.304	2.635	2.971	3.312	3.657	0
25							1.857	2.166	2.482	2.802	3.128	3.458	1
26							1.747	2.041	2.342	2.649	2.961	3.278	1

Log V = 2.45281 -3.08509 (log D) +0.82531 (log D) (log H)
S.D. of coeff. 0.179249 0.0728263
S.E. = 0.06559

Mean error = 15.5 percent
Ave. bias = -1.4 percent
Ave. deviation = 12.0 percent

Table 39.--*Gross cubic bark volume, entire stem--Douglas-fir*

D.b.h. (inches)	Total height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Sample size
	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	- - *Cubic*	*feet* - -	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -	*No. trees*
2	0.03	0.05	0.07	0.09	0.11	0.13							27
3	0.05	0.10	0.14	0.19	0.23	0.27							32
4	0.08	0.16	0.24	0.32	0.39	0.46	0.54						22
5		0.24	0.36	0.47	0.59	0.70	0.82						26
6		0.33	0.49	0.66	0.82	0.99	1.15	1.32	1.48				16
7		0.43	0.65	0.87	1.10	1.32	1.55	1.77	2.00				24
8		0.54	0.83	1.11	1.40	1.70	1.99	2.29	2.58				15
9		0.67	1.02	1.38	1.75	2.12	2.49	2.86	3.24				19
10			1.23	1.67	2.12	2.58	3.04	3.50	3.97				12
11			1.46	1.99	2.53	3.08	3.63	4.20	4.76	5.33			18
12			1.71	2.33	2.97	3.62	4.29	4.95	5.63	6.31	7.00		26
13			1.97	2.70	3.45	4.21	4.99	5.77	6.57	7.37	8.18		18
14				3.09	3.95	4.84	5.74	6.65	7.57	8.51	9.45		13
15				3.50	4.49	5.50	6.54	7.58	8.65	9.72	10.81		15
16				3.94	5.06	6.21	7.38	8.58	9.79	11.02	12.26		18
17				4.40	5.66	6.96	8.28	9.63	11.00	12.39	13.80		21
18				4.88	6.29	7.74	9.23	10.74	12.28	13.84	15.42		13
19					6.96	8.57	10.22	11.91	13.62	15.37	17.14	18.93	11
20						9.43	11.26	13.13	15.03	16.97	18.94	20.93	8
21						10.33	12.35	14.41	16.51	18.65	20.82	23.03	3
22						11.27	13.49	15.75	18.06	20.41	22.80	25.22	1
23						12.25	14.67	17.14	19.67	22.24	24.86	27.52	[illegible]
24						13.27	15.90	18.59	21.35	24.15	27.01	29.91	[illegible]
25							17.17	20.10	23.09	26.14	29.24	32.40	1
26							18.50	21.66	24.90	28.20	31.56	34.98	1

Log V = [illegible] +1.8[illegible] (log D) +0.77785[illegible] (log H) +0.285854 (log D) (log H)
S.D. of coeff. 0.1[illegible] 0.056642 0.061730
S.E. = 0.0[illegible]

Mean error = 14.0 percent
Ave. bias = [illegible] percent
Ave. deviation = 10.[illegible] percent

Table 40.--*Double bark thickness for stem sections of specified diameter--Douglas-fir*

D.o.b. (inches)	D.o.b. (10ths of inches)										D.o.b. (inches)
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
	Inches										
2	0.13	0.14	0.15	0.16	0.17	0.18	0.18	0.19	0.20	0.21	2
3	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30	0.30	3
4	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40	4
5	0.41	0.42	0.42	0.43	0.44	0.45	0.46	0.47	0.48	0.49	5
6	0.50	0.51	0.52	0.53	0.54	0.54	0.55	0.56	0.57	0.58	6
7	0.59	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.66	0.67	7
8	0.68	0.69	0.73	0.71	0.72	0.73	0.74	0.75	0.76	0.77	8
9	0.78	0.78	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.86	9
10	0.87	0.88	0.89	0.89	0.90	0.91	0.92	0.93	0.94	0.95	10
11	0.96	0.97	0.98	0.99	1.00	1.01	1.01	1.02	1.03	1.04	11
12	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.13	1.13	12
13	1.14	1.15	1.16	1.17	1.18	1.19	1.20	1.21	1.22	1.23	13
14	1.24	1.25	1.25	1.26	1.27	1.28	1.29	1.30	1.31	1.32	14
15	1.33	1.34	1.35	1.36	1.37	1.37	1.38	1.39	1.40	1.41	15
16	1.42	1.43	1.44	1.45	1.46	1.47	1.48	1.49	1.49	1.50	16
17	1.51	1.52	1.53	1.54	1.55	1.56	1.57	1.58	1.59	1.60	17
18	1.61	1.61	1.62	1.63	1.64	1.65	1.66	1.67	1.68	1.69	18
19	1.70	1.71	1.72	1.73	1.73	1.74	1.75	1.76	1.77	1.78	19
20	1.79	1.80	1.81	1.82	1.83	1.84	1.85	1.85	1.86	1.87	20

Values computed from the single-bark-thickness equation:

$T = -0.0276673 + 0.0461299\ (\text{D.o.b.})$
S.D. of coeff. 0.000372306
S.E. = 0.0659404
$R^2 = 0.895$
N = 1,815

Table 41.--Relationship between stump diameter and diameter at breast height (inches)

Stump diameter range, i.b.				D.b.h. class o.b.
Ponderosa pine	Douglas-fir	Western larch	Lodgepole pine	
1.7-2.6	1.7-2.6	1.7-2.6	1.4-2.4	2
2.7-3.6	2.7-3.7	2.7-3.5	2.5-3.6	3
3.7-4.6	3.8-4.7	3.6-4.5	3.7-4.7	4
4.7-5.5	4.8-5.7	4.6-5.5	4.8-5.8	5
5.6-6.5	5.8-6.8	5.6-6.4	6.0-7.0	6
6.6-7.5	6.9-7.8	6.5-7.4	7.1-8.1	7
7.6-8.5	7.9-8.8	7.5-8.3	8.3-9.3	8
8.6-9.5	8.9-9.9	8.4-9.3	9.4-10.4	9
9.6-10.5	10.0-10.9	9.4-10.3	10.5-11.6	10
10.6-11.5	11.0-11.9	10.4-11.2	11.7-12.7	11
11.6-12.5	12.0-13.0	11.3-12.2	12.8-13.9	12
12.6-13.5	13.1-14.0	12.3-13.2	14.0-15.0	13
13.6-14.5	14.1-15.0	13.3-14.0	15.1-16.1	14
14.6-15.5	15.2-16.1	14.2-15.1	16.3-17.3	15
15.6-16.5	16.2-17.1	15.2-16.1	17.4-18.4	16
16.6-17.5	17.2-18.2	16.2-17.0	18.6-19.6	17
17.6-18.5	18.3-19.2	17.1-18.0	19.7-20.7	18
18.6-19.4	19.3-20.2	18.1-19.0	20.8-21.9	19
19.5-20.4	20.3-21.3	19.1-19.9	22.0-23.0	20
20.5-21.4	21.4-22.3	20.0-20.9	23.1-24.2	21
21.5-22.4	22.4-23.3	21.0-21.9	24.3-25.3	22
22.5-23.4	23.4-24.4	22.0-22.8	25.4-26.5	23
23.5-24.4	24.5-25.4	22.9-23.8	26.6-27.6	24

Regression Equations

Species	Equation	S.D. of the Coefficient	S.E.	r
Ponderosa pine	D = -0.186432 + 1.0[illegible]9 S	0.0060791	[illegible]	0.997
Douglas-fir	D = -0.120125 + 0.96[illegible]7 S	0.0002658	[illegible]	0.997
Western larch	D = -0.255227 + 1.0[illegible]641 S	0.0003114	[illegible]	[illegible]
Lodgepole pine	D = -0.[illegible] + [illegible]73[illegible] S	[illegible]078	0.54636	[illegible]

D = d.b.h.

S = Stump diameter, inside bark

Table 42.--*Stand volume, cubic feet per acre--ponderosa pine*

Basal area (ft²)	Average height of dominant trees (feet)											
	20	30	40	50	60	70	80	90	100	110	120	130
20	144	216	288	360	432	504	576	648	720	792	864	936
40	288	432	576	720	864	1,008	1,152	1,296	1,440	1,584	1,728	1,872
60	432	648	864	1,080	1,296	1,512	1,728	1,943	2,160	2,376	2,592	2,808
80	576	864	1,152	1,440	1,728	2,016	2,304	2,592	2,880	3,168	3,456	3,744
100	720	1,080	1,440	1,800	2,160	2,520	2,880	3,240	3,600	3,960	4,320	4,680
120	864	1,296	1,728	2,160	2,592	3,024	3,456	3,887	4,320	4,752	5,184	5,616
140	1,008	1,512	2,016	2,520	3,024	3,528	4,032	4,536	5,040	5,544	6,048	6,552
160	1,152	1,728	2,304	2,880	3,456	4,032	4,608	5,184	5,760	6,336	6,912	7,488
180	1,296	1,944	2,592	3,240	3,888	4,536	5,184	5,832	6,480	7,128	7,776	8,424
200	1,440	2,160	2,880	3,600	4,320	5,040	5,760	6,480	7,200	7,920	8,640	9,360
220	1,584	2,376	3,168	3,960	4,752	5,544	6,336	7,128	7,920	8,712	9,504	10,296
240	1,728	2,592	3,456	4,320	5,184	6,048	6,912	7,775	8,640	9,504	10,368	11,232
260	1,871	2,807	3,743	4,680	5,615	6,551	7,487	8,424	9,360	10,295	11,231	12,167
280	2,016	3,024	4,032	5,040	6,048	7,056	8,064	9,072	10,080	11,088	12,096	13,104
300	2,160	3,240	4,320	5,400	6,480	7,560	8,640	9,720	10,800	11,880	12,960	14,040

Table 15.--Stand volume, cubic feet per acre--Lodgepole pine

Basal area (ft²)	Average height of dominant trees (feet)								
	20	30	40	50	60	70	80	90	100
20	184	286	368	460	552	644	736	828	920
40	368	552	736	920	1,104	1,288	1,472	1,656	1,840
60	552	828	1,104	1,380	1,656	1,932	2,208	2,484	2,760
80	736	1,104	1,472	1,840	2,208	2,576	2,944	3,312	3,680
100	920	1,380	1,840	2,300	2,760	3,220	3,680	4,140	4,600
120	1,104	1,656	2,208	2,760	3,312	3,864	4,416	4,968	5,520
140	1,288	1,932	2,576	3,220	3,864	4,508	5,152	5,796	6,440
160	1,472	2,208	2,944	3,680	4,416	5,152	5,888	6,624	7,360
180	1,656	2,484	3,312	4,140	4,968	5,796	6,624	7,452	8,280
200	1,840	2,760	3,680	4,600	5,520	6,440	7,360	8,280	9,200
220	2,024	3,036	4,048	5,060	6,072	7,084	8,096	9,108	10,120
240	2,208	3,312	4,416	5,520	6,624	7,728	8,832	9,936	11,040
260	2,392	3,588	4,784	5,980	7,176	8,372	9,568	10,764	11,960
280	2,576	3,864	5,152	6,440	7,728	9,016	10,304	11,592	12,880
300	2,760	4,140	5,520	6,900	8,280	9,660	11,040	12,420	13,800

Table 44.--*Stand volume, cubic feet per acre--western larch*

Basal area (ft^2)	Average height of dominant trees (feet)											
	20	30	40	50	60	70	80	90	100	110	120	130
20	144	216	288	360	432	504	576	648	720	792	864	936
40	288	432	576	720	864	1,008	1,152	1,296	1,440	1,584	1,728	1,872
60	432	648	864	1,080	1,296	1,512	1,728	1,943	2,160	2,376	2,592	2,808
80	576	864	1,152	1,440	1,728	2,016	2,304	2,592	2,880	3,168	3,456	3,744
100	720	1,080	1,440	1,800	2,160	2,520	2,880	3,240	3,600	3,960	4,320	4,680
120	864	1,296	1,728	2,160	2,592	3,024	3,456	3,887	4,320	4,752	5,184	5,616
140	1,008	1,512	2,016	2,520	3,024	3,528	4,032	4,536	5,040	5,544	6,048	6,552
160	1,152	1,728	2,304	2,880	3,456	4,032	4,608	5,184	5,760	6,336	6,912	7,488
180	1,296	1,944	2,592	3,240	3,888	4,536	5,184	5,832	6,480	7,128	7,776	8,424
200	1,440	2,160	2,880	3,600	4,320	5,040	5,760	6,480	7,200	7,920	8,640	9,360
220	1,584	2,376	3,168	3,960	4,752	5,544	6,336	7,128	7,920	8,712	9,504	10,296
240	1,728	2,592	3,456	4,320	5,184	6,048	6,912	7,775	8,640	9,504	10,368	11,232
260	1,871	2,807	3,743	4,680	5,615	6,551	7,487	8,424	9,360	10,295	11,231	12,167
280	2,016	3,024	4,032	5,040	6,048	7,056	8,064	9,072	10,080	11,088	12,096	13,104
300	2,160	3,240	4,320	5,400	6,480	7,560	8,640	9,720	10,800	11,880	12,960	14,040

Table 45.--*Stand volume, cubic feet per acre--Douglas-fir*

Basal area (ft²)	Average height of dominant trees (feet)											
	20	30	40	50	60	70	80	90	100	110	120	130
20	160	240	320	400	480	560	648	720	800	880	960	1,040
40	320	480	640	800	960	1,120	1,440	1,600	1,600	1,760	1,920	2,080
60	480	720	960	1,200	1,440	1,680	1,920	2,160	2,400	2,640	2,880	3,120
80	640	960	1,280	1,600	1,920	2,240	2,560	2,880	3,200	3,520	3,840	4,160
100	800	1,200	1,600	2,000	2,400	2,800	3,200	3,600	4,000	4,400	4,800	5,200
120	960	1,440	1,920	2,400	2,880	3,360	3,840	4,320	4,800	5,280	5,760	6,240
140	1,120	1,680	2,240	2,800	3,360	3,920	4,480	5,040	5,600	6,160	6,720	7,280
160	1,280	1,920	2,560	3,200	3,840	5,120	5,760	6,400	6,400	7,040	7,680	8,320
180	1,440	2,160	2,880	3,600	4,320	5,040	5,760	6,480	7,200	7,920	8,640	9,360
200	1,600	2,400	3,200	4,000	4,800	5,600	6,400	7,200	8,000	8,800	9,600	10,400
220	1,760	2,640	3,520	4,400	5,280	6,160	7,040	7,920	8,800	9,680	10,560	11,440
240	1,920	2,880	3,840	4,800	5,760	6,720	7,680	8,640	9,600	10,560	11,520	12,480
260	2,080	3,120	4,160	5,200	6,240	7,280	8,320	9,360	10,400	11,440	12,480	13,520
280	2,240	3,360	4,480	5,600	6,720	7,840	8,960	10,080	11,200	12,320	13,440	14,560
300	2,400	3,600	4,800	6,000	7,200	8,400	9,600	10,800	12,000	13,200	14,000	15,600

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Presents tables and equations for estimating total cubic volumes of wood, wood residue, and bark for ponderosa pine, lodgepole pine, western larch, and Douglas-fir. Tables represent second-growth trees 80 years old or less, ranging in size from 1-1/2 inches d.b.h. to the maximum diameter measured for the respective species.

KEYWORDS: volume estimation, yield tables, merchantable volume, residue volume

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in four northwest timber species: ponderosa pine, lodgepole pine, western larch, Douglas-fir. USDA For. Serv. Res. Pap. INT-196, 55 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

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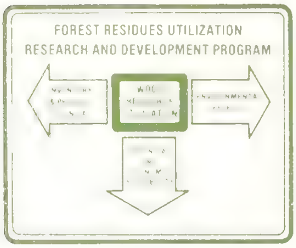
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WEIGHT AND DENSITY OF CROWNS OF ROCKY MOUNTAIN CONIFERS

James K. Brown

USDA Forest Service Research Paper INT-197
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

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RESEARCH SUMMARY

Relationships between live and dead crown weight and d.b.h. (ranging from 0 to 40 inches), crown length, tree height, and crown ratio are presented for 11 conifer species in the Rocky Mountains. D.b.h. was highly correlated with crown weight; however, for most species, addition of height, crown length, and especially crown ratio improved precision. Site index and stand density improved precision of estimates slightly for about one-half of the species. Crown ratio accounted for most of the differences in crown weight between dominant and intermediate crown classes. Relationships between bole weights and d.b.h. and height are presented for trees up to 4 inches d.b.h.

For partitioning estimates of crown weight into foliage, and branchwood diameter classes (0- to 0.24-inch, 0.25- to 0.99-inch, 1.00- to 2.99-inch and 3.00-inch and larger), accumulative fractions of foliage and branchwood and their relationship to d.b.h. are presented. Relationships between weights of foliage and branchwood by diameter classes, highly correlated with branch basal diameter, are included.

Bulk densities for foliage and branchwood of live crowns ranged from 0.04 to 0.14 lb/ft^3 and were approximately twice that for foliage alone. Bulk densities and crown moisture contents were greater in the upper crowns.

INTRODUCTION

Tree crowns are a vital component of forest biomass and the functioning of forest cosystems. The capability to estimate tree crown biomass is needed for evaluating ire behavior potential of forest fuels, productivity, nutrient cycling, fiber utilization, and interception of rainfall and radiation. The study reported here, initiated ut of the need to appraise forest fuels, deals with estimation of weights and sizes of rowns for commercial conifer species in the Rocky Mountains.

Objectives of the study were to:

1. Determine relationships for predicting weight of both dead and live tree rowns, from d.b.h., crown length, tree height, and crown ratio.

2. Determine the fractions of crown weight for foliage and branchwood by diameter ize classes of 0 to 0.24 inch (0 to 0.63 cm), 0.25 to 0.99 inch (0.64 to 2.53 cm), .00 to 2.99 inches (2.54 to 7.61 cm), and 3.00 inches (7.62 cm) and larger (fig. 1). termine the relationships among the fractions, species, and d.b.h.

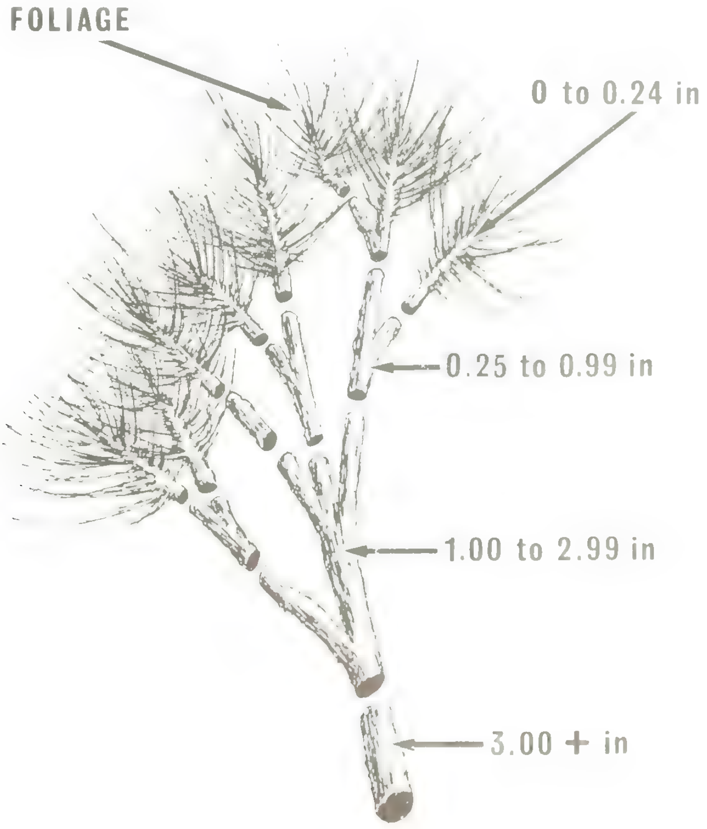

Figure 1.--Foliage and ranchwood size classes, for determining moisture ontent and size fractions of crown material.

3. Determine the bulk density of live tree crowns.

To appraise fire behavior potential of fuels one must know the weight of vegetat material and its surface area. Surface area can be estimated from the size distribut of biomass. Fuels of critical importance to land managers include downed woody resid left after harvesting and thinning of trees, or residues created by factors such as windstorms and snow breakage. To help land managers in the Rocky Mountain area appra the fuel and fire hazard of slash, a system for predicting slash weights and fire behavior potential has been developed (Puckett and others 1977). Slash weights are obtained from either a computer program for debris prediction[1] or a handbook that detai computational procedures for predicting slash fuels using tables of crown weight per tree (Brown and others 1977). The computer program requires tree inventory data as input and computes weights of foliage and branchwood, unmerchantable bole tips, and cull material. It is the most accurate method for predicting slash because it sums weights predicted for individual trees read into the program.

Rate of fire spread, area growth, intensity, flame length, and scorch height (Va Wagner 1973) are estimated in the system primarily using Rothermel's (1972) mathemati model of fire spread. Nomographs developed by Albini (1976) also provide a means for predicting fire behavior in slash.

Many studies have shown that crown weights of conifers and hardwoods can be predicted from bole diameter. However, except for lodgepole pine in Canada (Muraro 1966 Kiil 1967; Johnstone 1970) and Engelmann spruce in Colorado (Landis and Mogren 1975), only limited information exists for Rocky Mountain species (Storey and others 1955; Fahnestock 1960). Also, limited information, especially size distribution of branchw has been published on West Coast species (Kittredge 1944; Chandler 1960; Cole and Dic 1969; Storey 1969).

Storey and Fahnestock studied trees having dominant and codominant crowns rangin in d.b.h. from about 2 to 40 inches. Influence of stand density on crown weight was studied; however, site was shown to influence crown weight relationships (Storey and others 1955). Estimates of amount of foliage and branchwood were based on only a few observations. The study in this paper combines data by Fahnestock and Storey with considerable additional data, especially describing dead crown weights, size distribution of crown components, and live crown weights of trees less than 2 inches and grea than 20 inches.

The branchwood size classes under 3 inches correspond in increasing size to 1-, 10-, and 100-hour average moisture timelag classes for many woody materials (Fosberg 1970). These size classes are used as moisture timelag standards in the U.S. Nationa Fire-Danger Rating System (Deeming and others 1972). A moisture timelag is the amoun of time for a substance to lose or gain approximately two-thirds of the moisture abov or below its equilibrium moisture content. Appraisal of forest fuels is greatly facil tated when data on biomass are assimilated by these size classes. Once weight of foliage and branchwood by diameter classes is determined, surface area can be estimat using surface area-to-volume ratios for foliage (Brown 1970) and branchwood (Brown an Roussopoulos 1974). Weights must be converted to volumes using known or assumed valu of density (Brown 1974) for calculating surface area from volume and ratios of surfac area-to-volume.

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[1] Brown, J. K., and C. M. Johnston. 1976. Debris prediction system. Unpublishe report on file at the Northern Forest Fire Laboratory, Missoula, Montana.

METHODS

Trees of dominant and codominant crown classes (Society of American Foresters 1944) were studied for the following 11 species (abbreviations are used in tables and gures):

DF	Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
S	Engelmann spruce	*Picea engelmannii* Parry
GF	Grand fir	*Abies grandis* (Dougl.) Lindl.
LP	Lodgepole pine	*Pinus contorta* Dougl.
PP	Ponderosa pine	*Pinus ponderosa* Laws.
AF	Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
WH	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
L	Western larch	*Larix occidentalis* Nutt.
C	Western redcedar	*Thuja plicata* Donn
WP	Western white pine	*Pinus monticola* Dougl.
WBP	Whitebark pine	*Pinus albicaulis* Engelm.

Sample trees were selected to complement data on dominant and codominant crown asses gathered by Storey and others (1955) and Fahnestock (1960). Combining data onomized effort to develop prediction equations for a wide range of tree sizes.

Trees of intermediate and suppressed crown classes were studied for ponderosa pine, uglas-fir, grand fir, and western redcedar. These four species range from shade inlerant to tolerant. By studying them, the influence of shade tolerance and crown ass and their interaction on crown weight per tree could be examined. Throughout the ainder of this paper, "dominants" refer to both dominant and codominant crown asses and "intermediates" to both intermediate and suppressed crown classes. Most of e intermediates sampled were from the intermediate rather than the suppressed crown ss.

Fieldwork

ection of Trees

Trees were selected, ranging from seedling size to 34 inches d.b.h. The sampling a designed to include the natural variation in crown weight by selecting trees from nds on poor-to-good sites and from low-to-high stand density conditions throughout tern Montana and northern Idaho (fig. 2). The geographic distribution of trees is wn in appendix I. Trees were randomly picked; however, they were not accepted if y were (1) open-grown or "wolf" trees; (2) extremely lopsided in the crown; (3) ormed excessively by disease; (4) heavily defoliated; and (5) broken topped. These es applied to data by Storey and Fahnestock except that our sites and stand densitie e more restricted.

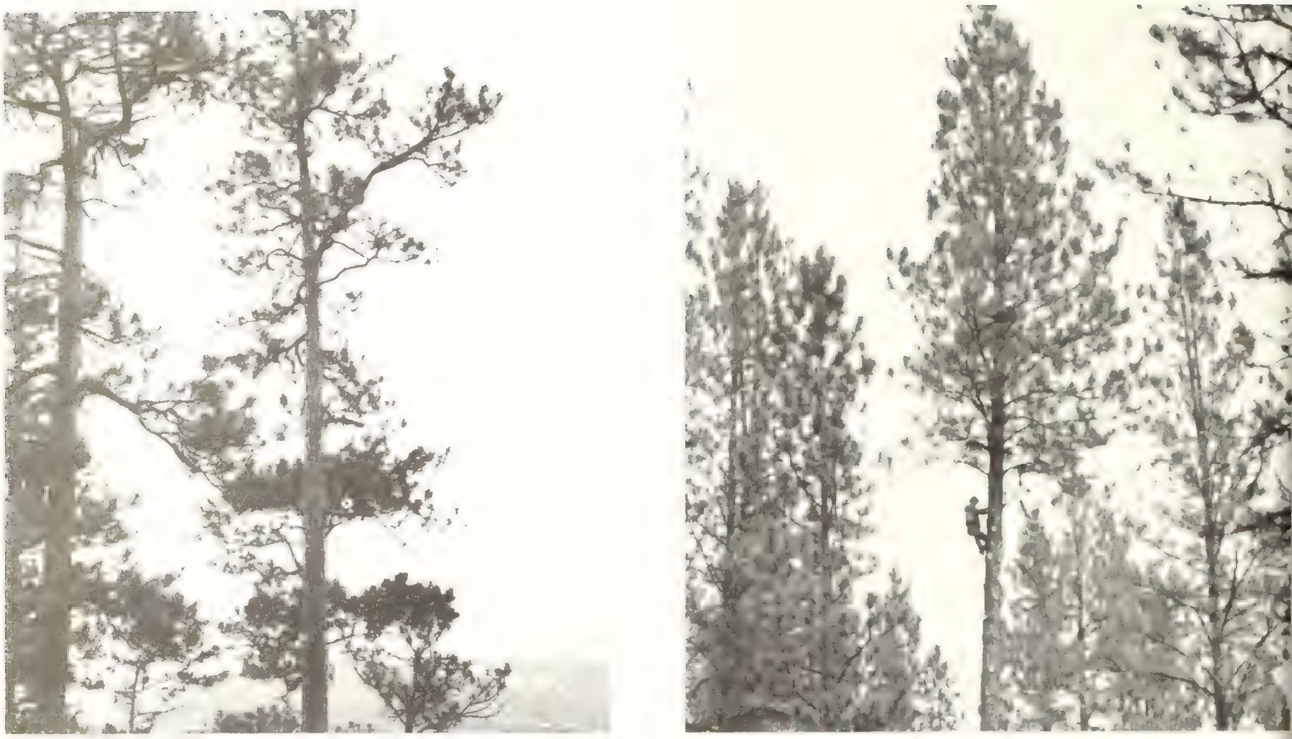

Figure 2.--These ponderosa pine show the variety of crown structure encountered in the sampling.

Measurements

On sample trees, crowns were visually divided into two or three horizontally partitioned live sections and one dead section that contained all dead branches within as well as below the live crown. Boundaries between live crown sections were located where diameters and lengths of branches changed distinctly. If changes in crown structure were not apparent, two crown sections were identified, with the boundary between them located near the middle of the crown. Weights, moisture contents, and crown volumes were determined by crown sections in order to characterize crown properties as accurately as possible.

Trees less than 6 inches d.b.h. were felled, then limbed; larger trees were climbed and limbed by workers using climbing spurs and safety belt (fig. 3). All branches were cut flush with the bole and separated by crown section. Basal diameters of all live branches were measured beyond the butt swell, 1 to 2 inches from the cut end.

Weights of each crown section and bole tips to 1-, 2-, 3-, 4-, and 6-inch diameter outside bark, were measured using spring scales of varying capacity, depending on amount of material. Canvas and nylon slings held the crown material for weighing. From each live section, a sample branch was randomly picked and from each dead section, a sample branch was picked that appeared average in size among the dead branches. The sample branches were divided into foliage and branchwood by size classes. The foliage and branchwood in each size class were weighed separately and moisture contents determined from duplicate samples ovendried at 100° C for 24 hours. In all, 22 to 34 moisture samples were taken for each tree. For small trees, most or all of the entire crown was often ovendried.

[illegible]
ith a safety rope to help
ontrol and direct the fall.

Trees were sampled from April to October during three successive field seasons. growth was included in all weight and moisture measurements. Once foliage and chwood of the current year's growth could be separated, they were thoroughly mixed old foliage and branchwood before moisture samples were taken. Thus, moisture ents were averages of old and new growth.

Most trees were sampled after new foliage had been produced. Variation in foliage ass due to sampling before and after growth of new foliage should be inconsequentia pt perhaps for ponderosa pine. For this species, which retains only 3 to 4 years' th of foliage, trees with and without new foliage were sampled. Thus, this variain foliage biomass was incorporated into the data.

Other measurements included:

--D.b.h. (outside bark);
--diameter outside bark at the base of live crown;
--total tree height (includes stump);
--length of bole tips to 1-, 2-, 3-, 4-, and 6-inch bole diameters;
--live crown length (base of the live crown was identified as the posit[illegible] the bole where a full crown could exist if lower branches were moved up to fill in open spaces);
--length of the lower one or two live crown sections;
--crown widths (average of two perpendicular measurements taken at the bottom of each crown section);
--length of needle-free cavity (measured from the base of live crown to a point along the bole where live foliage was encountered);
--width of needle-free cavity (average of two perpendicular measurements taken at the base of the live crown);

--age at ground level (on trees greater than about 6 inches d.b.h., age was measured at d.b.h. and increased by a constant 10 years to approximate age at ground level);

--site index (determined from site index curves and a 50-year base, USDA Forest Service Northern Region Compartment Prescription Handbook, October 1965); and

--basal area and trees per acre (for surrounding trees greater than 5 inches d.b. basal area and trees per acre were measured using one prism plot (20 basal area factor) having the sample tree at the center. For trees 5 inches and less in d.b.h., a 1/300-acre plot was used).

Many sample trees exceeded the d.b.h. range of Storey's and Fahnestock's data. A large number of trees within the d.b.h. range of their data were also sampled to help determine whether our data should be combined for analysis. Because Storey's and Fahnestock's data lacked weights of dead branches occurring below the live crown and lacked adequate information on size distribution of branchwood, some trees within the range of their data were sampled only for dead crown weights and counts of branch basa diameters for determining size distribution of crown material. For these trees, live crown weights were not recorded. A listing of data is in appendix II.

Analysis

Crown Weight and Bole Weight Per Tree

For each crown section, fresh crown weights were reduced to an ovendry basis, usi an average moisture content that was determined by weighting sample moisture contents foliage and the branchwood size classes by their respective weights. The foliage and branchwood weights were determined by means of step 2 in the section on foliage and branchwood fractions.

Live crown weights gathered in this study are probably slightly different from those of Storey and Fahnestock. In the studies by Storey and Fahnestock, which consis almost entirely of the same shared data, live crowns include dead branches found withi the live crown sections. In this study, live crowns contain only live branches. Most of the dead branch weight occurred below the live crown; thus, the inconsistency, if i exists, should be of minor consequence. Plots of crown weight over d.b.h. indicated that data from Storey, Fahnestock, and this study fit together smoothly and could be pooled.

For d.b.h. greater than 1.0 inch, the relationships between ovendry crown weights and tree characteristics were determined by first screening logical combinations of th following variables using a multiple regression computer program called REX (Grosenbau 1967):

$$w = f(d,\ d^2,\ d^3,\ h,\ dh,\ d^2h,\ c,\ dc,\ d^2c,\ R,\ dR,\ d^2R)$$
$$\ln w = f(\ln d,\ \ln h,\ \ln dh,\ \ln c,\ \ln dc,\ \ln R,\ \ln dR)$$

where

d = d.b.h., inch
h = tree height, ft
c = crown length, ft
R = crown ratio, (live crown length/tree height)10
w = weight of crowns, lb.

Unless otherwise stated, the definition of these terms applies throughout the paper. Variables such as crown width and diameter at the base of live crown were omitted from the analysis; however, all data are available for others to analyze if desirable.

Height data were missing for some of [illegible] trees. [illegible] ight was estimated from height-d.b.h. relationships of [illegible] own ratio was withheld from the screening process [illegible] g, program RFA provides a printout that lists [illegible] an square for all possible combinations of variables. [illegible] riable combinations having small residual mean squares were selected and details of ltiple regression analysis examined using the following criteria to determine the best tting equations. The equations should:

1. Give unbiased predictions for the data collected;
2. fit trees greater than approximately 4 inches d.b.h. reasonably well;
3. give positive predictions throughout the range of independent variables;
4. have as low a residual mean square as possible; and
5. give reasonable extrapolations beyond the range of sample data.

To determine whether site quality and stand density could improve prediction of ve crown weight beyond d.b.h., height, crown length, and crown ratio, variables from e "best-fitting equations" were screened together with site index, trees per acre, and sal area per acre. When regression coefficients for site and stand density variables rom equations selected in screening) were significant at the 0.90 probability level, ey were considered influential.

Trees having a d.b.h. less than 2 inches underwent a separate regression analysis, th height as the only independent variable. For trees 4 inches and less, functions r estimating total bole weight were determined in the same manner as for crown weights ept only d.b.h. and height were involved in the screening process.

[illegible]

For each tree, the fractions of dead branchwood by size class were computed assum- g that the proportion of weight in each size class for the dead sample branch repre- nted the size distribution for all dead branches. However, for live crowns, fractions foliage and branchwood by size classes were determined in four steps involving all anches on a tree:

1. Simple linear regressions between weights of each crown component and branch al diameter were determined using sample branch data. Besides branches randomly ked from each crown section, additional branches were collected to assure having anches of large basal diameters. Natural log transforms of dependent and independent aiables were used and weights estimated from:

$$y = e^{(a + b(\ln X) + \frac{s^2}{2})}$$

hre

y = ovendry weight of foliage or branchwood by size classes, lb
X = basal diameter of branch, inch
s^2 = sample variance of the logarithmic equation used to correct for an approximate bias in converting logarithmic estimates to arithmetic units (Baskerville 1972).

2. Solving equation (1) for tallies of branches by basal diameters, weights of oiage and branchwood by the 0- to 0.24-inch, 0.25- to 0.99-inch, 1.00- to 2.99-inch, nd 3.00-inch-and-over classes were computed for the live crown sections of sample trees

3. Calculated weights of foliage and branchwood components were then adjusted so that the sum of all component weights equaled the weight of each crown section actuall measured in the field, as shown in equation (2).

$$y'_{ij} = \sum_{k=1}^{n} y_{ijk} R_j \qquad (2)$$

where

y' = adjusted weights
y = calculated weight from equation (1)
R = ratio of measured weight for entire crown section to sum of estimated weights for all crown components
i = index for foliage and branchwood size classes
j = index for crown sections
k = index for individual branches
n = number of branches in a crown section.

Lastly, the adjusted weights of each crown component were summed for the entire tree.

4. For each sample tree, the following accumulative fractions of total live crow weight were calculated:

P_1 = foliage

$P_2 = P_1$ + 0- to 0.24-inch branchwood

$P_3 = P_2$ + 0.25- to 0.99-inch branchwood

$P_4 = P_3$ + 1.00- to 2.99-inch branchwood.

A similar set of fractions was calculated for dead branchwood but without foliage These fractions were subjected to a least squares curve fitting analysis with d.b.h. a the independent variable. The fraction of any branchwood component can be obtained as the difference between two accumulative fractions. Fitting fractions of branchwood by individual size classes to d.b.h. was attempted, but for some sets of data it was difficult to find precise-fitting equations. Thus, accumulative fractions were used because they provided well-behaved data sets for curve fitting.

Fractions for dividing small tree boles and unmerchantable bole tips into diamete size classes of 0 to 0.99 inch, 1.00 to 2.99 inches, and 3.00 inches and greater were computed from volume estimates of each size class. Volume of each size class was determined using length and diameter measurements of tip pieces. Tip pieces were considered as cones and other pieces as frustums of cones.

Bulk Density of Crowns

Bulk density of live crowns was computed using ovendry weights of foliage alone, and foliage and all branchwood together. Bulk density of foliage was computed two ways using crown volume determined with and without the needle-free cavity. Crown volumes were computed from measurements of length and width of the top crown section and the two lower crown sections combined. Top sections were considered as either cones or paraboloids, depending on a shape designation assigned in the field. Lower sections were treated as frustums of right cones. The needle-free cavity was treated as a paraboloid.

RESULTS AND DISCUSSION

Crown Weights

[illegible]

Equations for live crown weight are presented in table 1 and [illegible] n table 2. In the tables, LN is the base of natural logarithms. [illegible] quation containing d.b.h. as the only independent variable is presented because often .b.h. may be the only information available for estimating weight. For some species, .b.h. alone provided the best-fitting equation; however, where addition of tree height rown length, or crown ratio to the equation improved fit, these equations are also resented. Although the equations in tables 1 and 2 were [illegible] ther equation forms and combinations of independent variables gave good fits of the ata. I found, as Crow (1971) reported, that the best [illegible] ets. Several curve forms can fit about equally well.

Intercept regression parameters that were [illegible] imes retained in the equations when the fit for trees of small d.b.h. was improved. though the regression constants in tables 1 and 2 [illegible] vel of at least 0.05, [illegible] ssible. Extrapolation of equations beyond about 40 inches d.b.h. risks substantial rror.

The data for Douglas-fir were particularly difficult to fit; hence, two equations overing different ranges in d.b.h. are presented. [illegible] d myself are probably from different populations. Live crown weight populations thin the Pacific Northwest are [illegible]

This study showed that to achieve a good fit for prediction, actual deviation tween observed and predicted observations should be examined. [illegible] t find a function that fits the data [illegible] R values, as an indicator of good fit, [illegible]. ture on crown weight prediction suggests that some studies would profit from a reevalua-tion of prediction functions to improve accuracy, especially at the outer ends of their data range.

In equations for 8 of the 11 species, crown ratio or crown length accounted for a significant reduction [illegible] at accounted for by d.b.h. [illegible] riation than either height or crown [illegible] und by Loomis and others [illegible] ight, crown length, and crown ratio [illegible] to influence live crown weight [illegible] by Storey and others [illegible] ngth can largely [illegible] for four species and [illegible] an effective variable for the [illegible] gnificant for about one-half of the species. [illegible] ion beyond that accounted for by [illegible]

Table 1.--*Live crown weight equations for dominant and codominant trees greater than 1-inc d.b.h.*

Species	R^2	MSR[1]	$\left(\frac{\sqrt{MSR}}{\bar{Y}}\right)100$	n	Range in d.b.h.[2]	Equations
		Lb^2	*Percent*		*Inches*	
GF	0.95	26,100	57	35	1-40	[3] w = EXP[1.3094 + 1.6076(lnd)]
L	.96	3,684	38	45	1-35	[3] w = EXP[0.4373 + 1.6786(lnd)]
S	.96	11,470	36	29	1-29	[3] w = EXP[1.0404 + 1.7096(lnd)]
AF	.95	276	25	16	1-13	w = 1.066 + 0.1862(d^2R)
	.84	947	46			w = 7.345 + 1.255(d^2)
LP	.88	600	22	45	1-16	w = 0.02238(d^3) + 0.1233(d^2R) - 2.00
	.88	1,065	30			[3] w = EXP[0.1224 + 1.8820(lnd)]
WP	.97	956	24	44	1-43	w = 0.09470(d^2R)
	.95	1,567	31			w = 3.65 - 0.04534(d^3) + 0.01233(d^2h)
	.95	3,279	45			[3] w = EXP[0.7276 + 1.5497(lnd)]
WBP	.99	0.889	5	10	1-8	w = 0.65 + 0.06056(d^3) + 0.05477(d^2R)
	.98	3.89	14			w = 0.8371(d^2) - 1.00
C	.97	7,965	46	34	1-37	w = EXP[1.7273(lndR) - 2.8086]
	.96	10,070	52			w = EXP[0.8815 + 1.6389(lnd)]
PP	.97	37,560	36	40	1-34	[3] w = EXP[2.2812(lnd) + 1.5098(lnR) - 3.0957
	.95	82,570	53			[3] w = EXP[0.2680 + 2.0740(lnd)]
DF	.95	4,712	28	41	1-34	w = 27.94 - 0.008695(d^2h) + 0.02839(d^2c), for d ≥15 inches, and R ≥5
	.93	21,620	64			[3] w = EXP[1.1368 + 1.5819(lnd)], for d <17
	.85	13,460	48			w = 1.0237d^2 - 20.74, for d ≥17 inches
WH	.98	809	15	27	1-32	w = 0.3729(d^2) + 0.2840(dc) - 0.005525(d^2c - 4.50
	.98	1,076	17			w = 3.60 - 1.5450(d^2) + 0.01734(d^3)+0.3880
	.98	4,605	36			w = EXP[0.7218 + 1.7502(lnd)]

---

[1] MSR indicates mean square residuals. For logarithmic functions, MSR was calculat as $\Sigma(P-O)^2/df$, where P and O are predicted and observed values transformed to arithmetic units and df is the residual degrees of freedom.

[2] Range in d.b.h. for sample trees.

[3] These equations are of the form lny = a + blnX + (mean square error/2). The latte term corrects for bias in transforming logs and is included in the intercept term in the equations. The intercept term was adjusted by (mean square/2) when the summation of predicted minus observed values in arithmetic units showed less bias with the correction term than without it.

[illegible]

R	MSR[1]	$\left(\frac{\sqrt{MSR}}{\bar{y}}\right)100$	[illegible]	Range in d.b.h.[2]	[illegible]
		[illegible]		[illegible]	
0.95	304	42	[illegible]	1-20	[illegible]
.93	187	62			[illegible]
					[illegible]
.89	551	138	14	1-23	[illegible]
.87	992	167			[illegible]
.95	11.2	36	16	1-13	[illegible]
.93	116	104			[illegible]
.91	67	102			[illegible]
					[illegible]
				1-16	w = (0.026(d) - 0.025)(live crown wt), for [illegible]
					[illegible]
.80	184	135	11	1-[illegible]	[illegible]
.86	.93	48	13	1-11	w = 0.001713(d^2c) + 0.33
.85	.98	54			w = 0.001397(d^2h) + 0.28
.82	1.16	60			w = 0.06117(d^2)
.98	91.2	25	[illegible]	1-[illegible]	[illegible]
.87	1,590	79	[illegible]	1-34	[illegible]
.98	159	28	21	1-34	[illegible]
.91	1,151	50			w = 0.01094(d^2)
.92	237	140	20	1-21	[illegible]
.84	297	227			[illegible]

---

[1] MSR indicates mean square residual[illegible] (P-O)²/df, where P and O are predicted and [illegible] and df is the residual degrees of freedom.

[2] Range in d.b.h. for sample trees.

[3] Corrections for logarithmic transformation [illegible] more bias than they eliminated. [illegible]

[4] This species retains little [illegible] weights ranged from 0.1 to 5.1 lb and averaged 1.1 lb.

[5] The equation for LP was from [illegible] regression analysis.

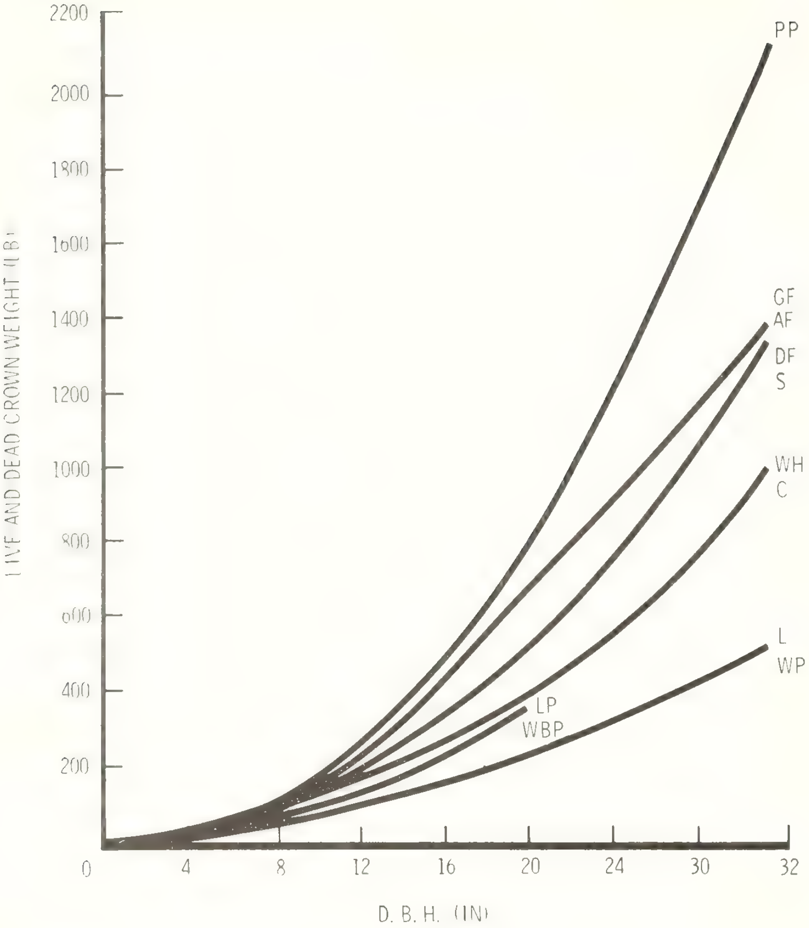

Figure 4.--Live and dead crown weight related t d.b.h. for groups of species having similar relationships.

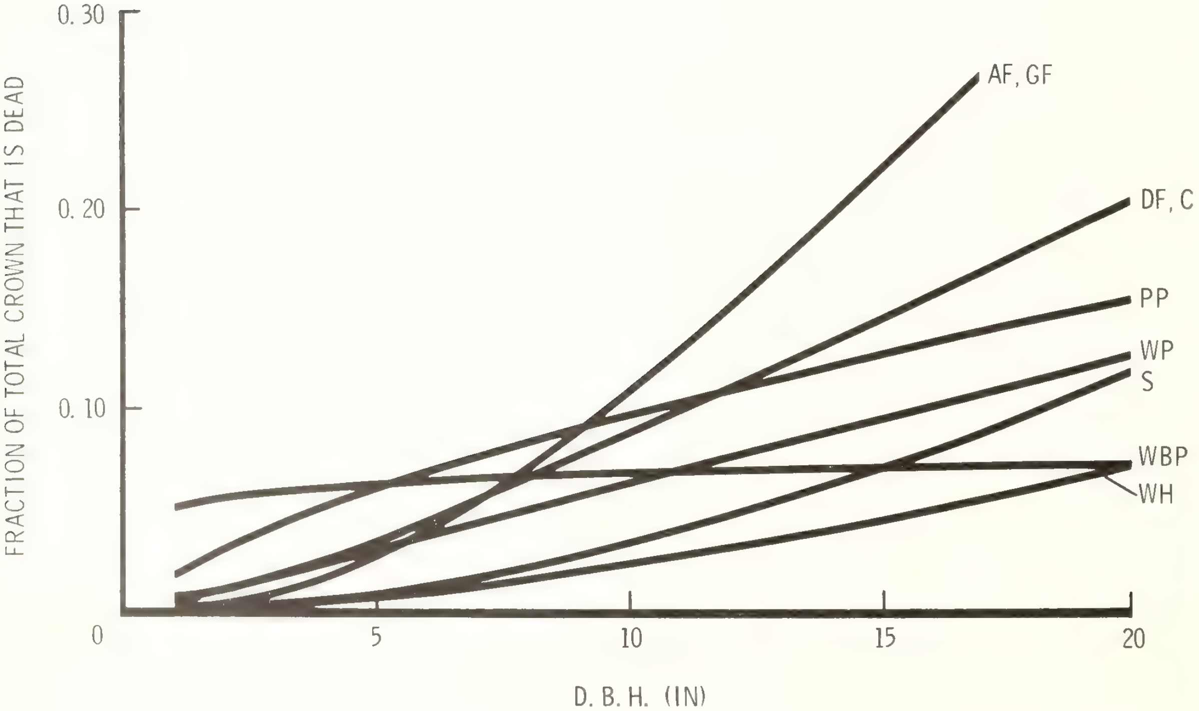

Figure 5.--The fraction of total crown that is dead (live plus dead branches) for dominants. The curves were plotted from equations in tables 1 and 2. Two species represented by one curve were averaged.

Relationship between total crown [illegible] ure 4. Crown weight [illegible] rcent of the [illegible] erance is unrelated to [illegible] nderosa pine, a relatively [illegible] ge diameters. [illegible] stern larch.

[illegible] species, the fraction of total crown [illegible] creasing d.b.h. and [illegible] expected because as trees age, branches die and can accumulate. Branch retention ries significantly among species. However, [illegible] es not appear readily explainable. The curve for grand fir and subalpine fir should el off for trees larger than about 15 inches d.b.h. Larch and lodgepole pine are tted from figure 5 because of negligible branchwood for larch and insufficient data lodgepole pine.

[illegible]

Separation of data into two groups, one for trees greater than 1 inch d.b.h. and for smaller trees, permitted derivation of more accurate relationships than handling data together. To obtain adequate data for the small tree group, trees less than iches d.b.h. were treated as a data set with tree height as an independent variable. xpected, live crown weight was strongly related to tree height (table 3). Generally, wns of shade-tolerant [illegible] eption is the shade tolerant western [illegible] h. The tolerant trees were also older [illegible] ain the major differences in weight. Dead crown weight was essentially negligible. all species, it averaged 1 percent of total crown weight. The largest dead percent- was 2.4 for western larch, which is interesting because larch greater than 2 inches h. supported the least quantity of dead branches among all species.

[illegible]

[illegible] best-fitting equations for [illegible] a crown weights are shown in table 4.

As species increased in shade tolerance, the difference between total crown weights ominants and intermediates decreased (fig. 6). This was also true for live crown ihts. For western redcedar, the most tolerant of the four species studied, crown as essentially had no effect on total weight and live crown weight per tree. For nerosa pine, the most intolerant species, total crown weight of intermediates was ot one-half of that for dominants.

For ponderosa pine and Douglas-fir, differences in crown weights between crown ases can be explained by crown ratio and crown length. For these species (trees t 12 inches d.b.h.), crown ratio averaged 7.2 for dominants and 5.3 for intermediates. tst of differences between pooled residuals of dominants and intermediates and resid- l from a composite regression showed that weight predictions based on d.b.h. were gificantly different (95 percent confidence level). However, weight predictions sd on d.b.h. and crown ratio were from a common population. Although crown ratio and on length accounted for differences in weight between crown classes, the proportions bliage and certain branchwood size classes varied considerably by crown class.

The importance of crown ratio in predicting weights of grand fir and western red- ar was unclear. The test of differences in live and total crown weight between row classes was nonsignificant for grand fir and significant for western redcedar.

Table 5.--[illegible] of trees less than 2 inches d.b.h.

Species	R^2	MSR[1]	n	Range in ht	Equations	Weight at 5 ft	Weight at 10 ft
		Lb		- -*Ft*- -		- - *Lb* - -	
					DOMINANTS		
DF	0.83	1.156	11	3.7-11.4	$w = EXP[-4.212 + 2.7168(\ln h)]$	1.2	7.7
S	.94	7.290	12	1.9-10.4	$w = EXP[-3.932 + 2.571(\ln h)]$[2]	1.2	7.3
AF	.90	1.343	13	2.5- 9.9	$w = EXP[-3.335 + 2.303(\ln h)]$[2]	1.4	7.2
C	.90	1.908	12	1.8-10.1	$w = 0.04833(h^2)$	1.2	4.8
GF	.79	3.138	12	3.1-14.0	$w = 0.4284(h)$	2.1	4.3
PP	.81	1.235	12	2.3-10.0	$w = 0.3451(h)$	1.7	3.4
WP	.97	0.190	13	2.8-11.5	$w = 0.3292(h)$	1.7	3.3
LP	.96	.220	12	1.6-13.1	$w = 0.03111(h^2)$	0.8	3.1
WBP	.93	.085	10	2.5-10.0	$w = 0.070 + 0.02446(h^2)$	.7	2.5
WH	.91	2.221	12	3.6-13.6	$w = EXP[-5.126 + 2.563(\ln h)]$[2]	.4	2.2
L	.80	1.230	12	2.8-18.0	$w = 0.1128(h) + 0.00813(h^2)$	.8	1.9
					INTERMEDIATES		
GF	.85	.374	9	3.7- 9.5	$w = 0.0538(h^2)$	1.3	5.4
C	.96	.142	11	3.7-10.4	$w = 0.0307(h^2)$	.8	3.1
DF	.66	.985	10	3.6-15.6	$w = EXP[-2.8065 + 1.4802(\ln h)]$[2]	.6	1.8
PP	.35	.268	10	3.9-14.6	$w = EXP[-2.7297 + 1.1707(\ln h)]$[2]	.4	1.0

---

[1] MSR indicates mean square residuals. For logarithmic functions, MSR was calculated as $\Sigma(P-O)^2/df$, where P and O are predicted and observed values transformed to arithmetic units and df is the residual degrees of freedom.

[2] These equations are of the form $\ln y = a + b\ln X + (\text{mean square error}/2)$. The latter term corrects for bias in transforming logs and is included in the intercept term in the equations. The intercept term was adjusted by (mean square/2) when the summation of predicted minus observed values in arithmetic units showed less bias with the correction term than without it.

Table 4.--[illegible]

[illegible]	Crown portion	R^2	MSR[1]	[illegible]	[illegible]	[illegible]		[illegible]
FP	Live	0.90	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
	Dead	.81	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
	Combined	.9[illegible]	[illegible]	60	[illegible]	[illegible]		[illegible]
[illegible]	Live	.96	[illegible]	[illegible]	[illegible]	11		[illegible]
	Live	.90	1,[illegible]	[illegible]	[illegible]	11		EM[0.1508 + 1.86[illegible]
	Dead	.[illegible]	206.0	110	[illegible]	[illegible]		[illegible]
	Combined	.94	1,[illegible]	[illegible]	[illegible]	1.11		[illegible]
CH	Live	.9[illegible]	731.0	[illegible]	[illegible]	[illegible]		[illegible]
	Dead	.8[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2/	[illegible]
	Combined	.94	[illegible]	43	15	[illegible]		[illegible]
[illegible]	Live	.91	1,041	[illegible]	[illegible]	[illegible]		[illegible]
	Dead	.9[illegible]	24.4	74	[illegible]	[illegible]		[illegible]
	Combined	.9[illegible]	1,077	[illegible]	[illegible]	[illegible]	2/	[illegible]

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[1] MSR indicates mean square [illegible] calculated as (P-O) [illegible], where [illegible] formed to arithmetic units [illegible]

[2] These equations are of [illegible] The latter term corrects for bias [illegible] intercept term in the equation. [illegible] when the summation of predicted minus observed values in arithmetic units showed less bias with the correction term than without it.

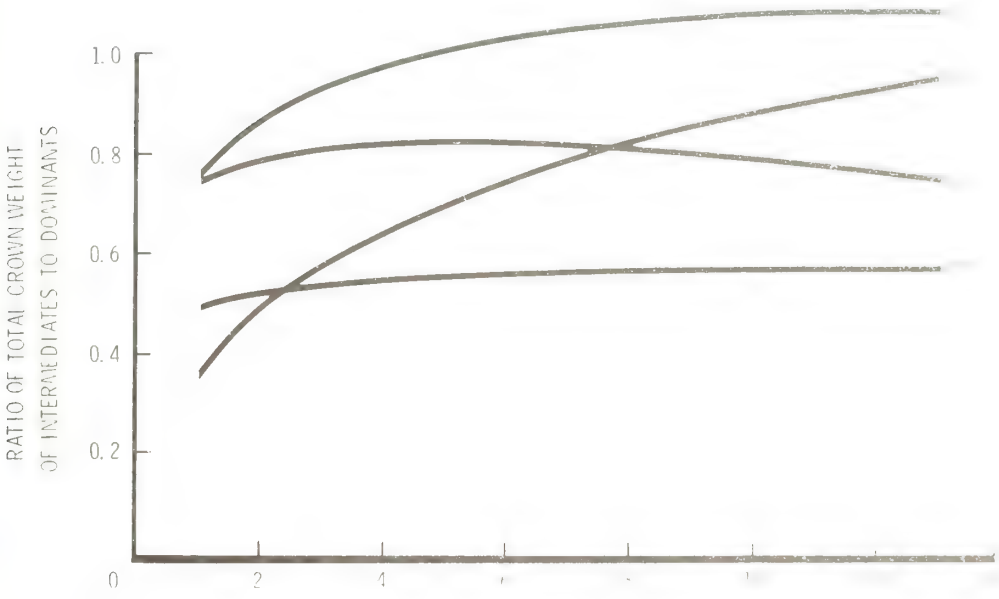


Figure 6.--Ratio of total crown weight [illegible] of d.b.h. The ratios [illegible]

For cedar, the differences in weight estimates seem small enough to ignore from a practical point of view. For both species, crown ratio was sampled over a narrow range thus, evaluation of the relationship between crown weight and crown ratio was restraine

Over the range of d.b.h. studied, intermediates supported approximately 2 to 6 times as much dead branch weight as dominants. Douglas-fir intermediates had 4 to 6 times as much dead branchwood as dominants, the highest ratio of any species. Ponderos pine showed the lowest ratio, the intermediates supporting nearly 2 times as much deadwood as the dominants. The ratios increased substantially for trees less than 3 inches d.b.h. because little dead branchwood was found on small dominants. Although the percent of total crown that is dead increased with increasing d.b.h. for dominants, it appeared nearly constant for intermediates. For intermediates 2 inches and greater in d.b.h., the dead percentage for ponderosa pine and Douglas-fir averaged about 25 percen and for grand fir and western redcedar about 12 percent.

The influence of crown class on crown weight per tree suggests that for activities such as fuel appraisal, crown class can be disregarded for estimating crown weights of tolerant species. However, for intolerant species, weight estimates should be partly based on either crown class or crown ratio. Likewise, for estimation of total stand biomass involving intolerant or moderately tolerant species, crown class or crown ratio should be accounted for in estimating crown weight.

Trees 1 inch and less in d.b.h..--Except for grand fir, live crowns of intermediat under 2 inches d.b.h. weighed less than crowns of dominants (table 3). For trees great than 8 feet in height, the equation for grand fir intermediates predicts greater crown weights than the equation for dominants. This holds true even after eliminating intermediate No. 835 from the regression analysis because it appeared unusually heavy. Apparently, several intermediates, at least 35 to 45 years of age and 8 to 10 feet tall, were responsible for the large weight predictions of intermediates. Although short in height, they had bushy crowns containing lots of foliage and branchwood. At comparable heights, the faster grown dominant trees contained less branchwood and foliage.

Similar to the trees greater than 1 inch d.b.h., crown weights for intolerant species were considerably greater for dominants than for intermediates. For tolerant species, crown weight predictions differ only a small amount between crown classes (table 3). Crown ratios averaged less for intermediates of all species and probably account for some of the weight differences between crown classes.

The percent of total crown that is dead varied considerably among individual trees The percent dead for the intermediates averaged:

Species	*Percent dead*
Ponderosa pine	18.3
Douglas-fir	11.8
Western redcedar	6.0
Grand fir	2.6

The percent dead of intermediates is substantially greater than for the dominants, probably due to effects of shading. Among the intermediates, the tolerant species exhibited a smaller fraction of dead branchwood.

Bole Weights

The same procedure used in selecting equations for crown weights was applied to bole weights (including bark) for trees 4 inches and less in d.b.h. (table 5). Up to 2 inches d.b.h., estimated bole weights for all species are almost the same; however, beyond 2 inches d.b.h., large differences among some species appear (fig. 7). For

Table 5. [illegible]

Species	R	MSR[1]	$\left(\frac{\sqrt{MSR}}{\bar{Y}}\right)100$	n	Equation
			DOMINANT		
S	0.96	0.7472	17	10	[illegible]
F	.99	.4056	11	12	[illegible]
P	.96	1.378	20	11	[illegible]
P	.97	.07645	14	8	$w = 1.49 - 2.388(d) + 2.297(d^2)$
P	.98	.2868	13	15	[illegible]
	.99	.1849	6	13	$w = 1.436(d) + 0.3326(d^2)$
H	.99	.0926	7	12	$w = 0.62 + 0.8024(d^2) + 0.1724(d^3)$
H	.98	.6754	15	12	$w = 0.31 + 0.8334(d) + 0.06819(d^2h)$
	.97	.9778	18	12	[illegible]
	.99	.4169	9	12	$w = 0.65 + 0.1004(d^2h)$
	.99	1.113	14	12	$w = 0.96 + 0.6532(d^3)$
F	.99	.3078	8	12	$w = 0.28 + 0.02692(d^2h) + 0.1912(dh)$
	.99	.7491	12	12	[illegible]
BP	.95	2.718	26	8	[illegible]
	.91	4.866	34	8	[illegible]
			INTERMEDIATE		
	.97	.8852	21	[illegible]	$w = -0.88 +$ [illegible]
	.92	5.271	49	11	$w = 0.20 + 0.07058(d^2h)$
	.79	13.27	77	11	$w = 0.74 + 0.4006(d^2)$
	.97	2.497	23	10	$w = 0.52 + 1.350(d^2)$
	.97	1.467	24	8	[illegible]
	.87	7.110	52	8	[illegible]

---

[1] MSR indicates mean square residuals. For logarithmic functions, MSR was calculated as [illegible]/df, where [illegible] arithmetic units and df is the residual degrees of freedom.

[2] This equation is of the form lny = a + blnX + (mean square error/2). The latter term corrects for bias in transforming logs and is included in the intercept term in the equation. The intercept term was adjusted by (mean square/2) when the summation of predicted minus observed values in arithmetic units showed less bias with the correction term than without it.

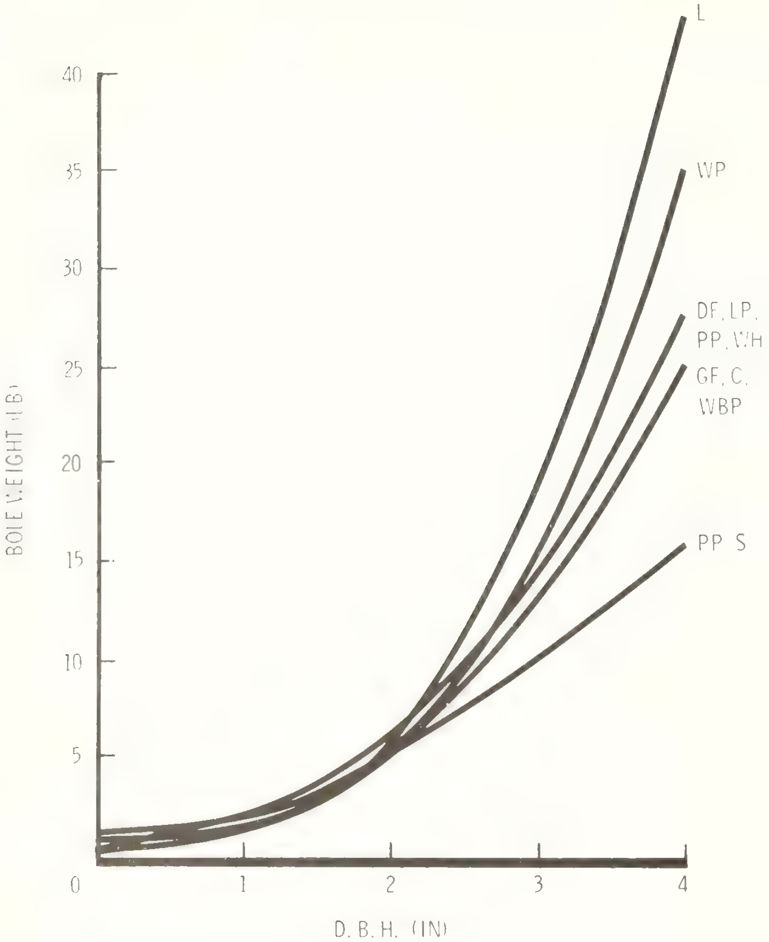


Figure 7.--Weights of boles for dominants 4 inches and less in d.b.h. Almost all estimate for individual species differ from the group average by less than 20 percent of the group average.

dominants, the extremes in estimated weights at 4 inches d.b.h. are 43 lb for western larch and 16 lb for Engelmann spruce. Differences in wood density and tree height account for the difference in weight.

Limited data from this study suggest that bole weights of intermediates tend to weigh more than dominants. Except for western redcedar, equations in table 5 yield greater bole weights for intermediates than dominants. For western redcedar and ponderosa pine, differences in bole weights between dominants and intermediates were statistically nonsignificant according to a test of differences between pooled residuals of dominants and intermediates and a composite regression (90 percent confidence level). For grand fir and Douglas-fir, bole weights were significantly different between dominants and intermediates (99 percent confidence level).

Whole Tree Weights

For seedlings and small saplings, separation of crown weights from bole weights may be undesirable for some purposes. Thus, the equations in table 6 were derived to estimate whole tree weights. Weight estimates for individual species are within about 15 percent of the average for the group of species. Weights of intermediate grand fir can be predicted using the equation for dominant grand fir.

Ponderosa pine, Douglas-fir, Engelmann spruce, and subalpine fir weighed noticeably more than the other species (fig. 8). For trees over 5 ft tall, average d.b.h. and age of the heaviest species group were greater than the other species. Although rate of height growth for the heaviest species group was less, more dry matter in crowns and boles had been produced. Proportions of foliage and branchwood are summarized in appendix III.

[illegible]

[illegible]	[illegible]	[illegible] 1/	[illegible]	[illegible]	[illegible]
[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]			[illegible]
[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1/ [illegible] calculated as $\Sigma(P-O)^2/df$, where P and O are predicted and observed values transformed to arithmetic units and df is the residual degrees of freedom.

2/ [illegible] The latter term corrects for bias in transforming logs and is included in the intercept term in the equations. The intercept term was adjusted by (mean square/2) when the summation of predicted minus observed values in arithmetic units showed less bias with the correction term than without it.

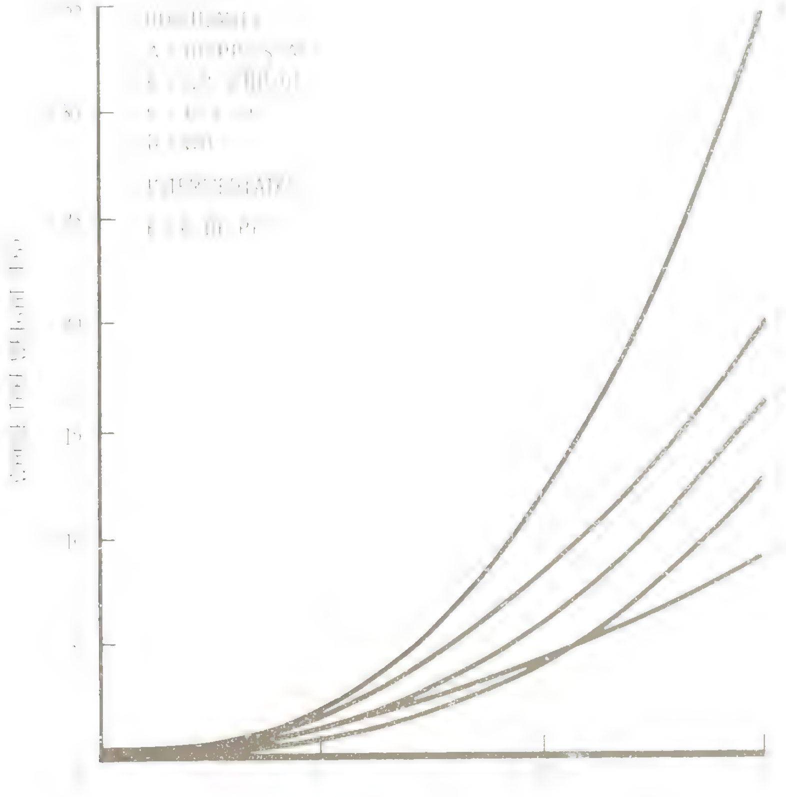


Figure 8.--Whole tree weights
or trees less than 15
eet tall.

Table 7.--*Simple linear regressions for estimating weight of foliage and branchwood components of individual branches from dominant and codominant trees. Regressions are of the form lnw = a + b(lnd) where w = weight, lb; d = branch basal diameter, inches. Bias was corrected as shown in equation (1)*

Statistic	DF	GF	AF	WH	C	S	L	PP	LP	WP	WBP
					FOLIAGE						
a	-0.6747	-0.4568	-0.6519	-0.5089	-0.6891	-0.5180	-1.545	-0.9641	-0.9175	-1.128	-0.9265
b	2.121	2.204	2.076	2.117	2.114	2.169	2.023	2.035	2.260	2.018	2.292
n	64	65	56	61	69	44	51	48	47	64	40
r	.95	.92	.90	.96	.95	.95	.94	.92	.87	.94	.88
					0 TO 0.24 INCH						
a	-1.465	-1.506	-1.233	-1.192	-2.253	-1.082	-1.228	-3.424	-1.224	-1.626	-1.844
b	2.000	2.083	2.268	2.083	2.021	2.336	2.158	1.180	2.490	2.202	1.915
n	56	60	52	57	63	38	53	39	45	61	37
r	.96	.93	.91	.96	.93	.96	.95	.74	.95	.91	.70
					0.25 TO 0.99 INCH						
a	-.9315	-1.120	-.5650	-.8144	-1.311	-.9377	-.9763	-1.070	-1.077	-1.378	-1.008
b	2.126	2.690	3.268	2.390	2.192	2.694	2.426	2.399	2.607	2.638	2.664
n	40	[illegible]	35	30	44	30	23	41	28	45	24
r	.91	.91	.91	.86	.89	.92	.87	.94	.92	.91	.79
					1.00 TO 2.99 INCHES						
a	-1.000	-1.485	-1.675	-1.168	-1.318	-.9333	-.7957	-1.125	-1.159	-2.894	-2.180
b	3.002	3.960	7.047	3.912	3.536	3.184	1.861	2.490	3.199	5.106	3.351
n	20	13	9	12	15	12	10	18	11	14	4
r	.83	.83	.79	.85	.96	.78	.63	.89	.80	.91	.76
					3.00 INCHES AND GREATER[1]						
a								-3.687			
b								4.363			
n								11			
r								81			

---

[1] For species other than PP, material 3 inches and larger either did not exist or was approximated by means other than regression analysis.

Branch Weights

Using logarithmic transformations, weights of foliage and branch components for individual branches were highly correlated with branch basal diameters, as shown in table 7 for dominants and table 8 for intermediates. The pattern of weight curves for individual branch components shown in figure 9 for grand fir is typical of most species. Except for western larch, the 1- to 3-inch branchwood class has the steepest regression slopes showing a rapid increase in the weight of the largest diameter material as branch basal diameter increases.

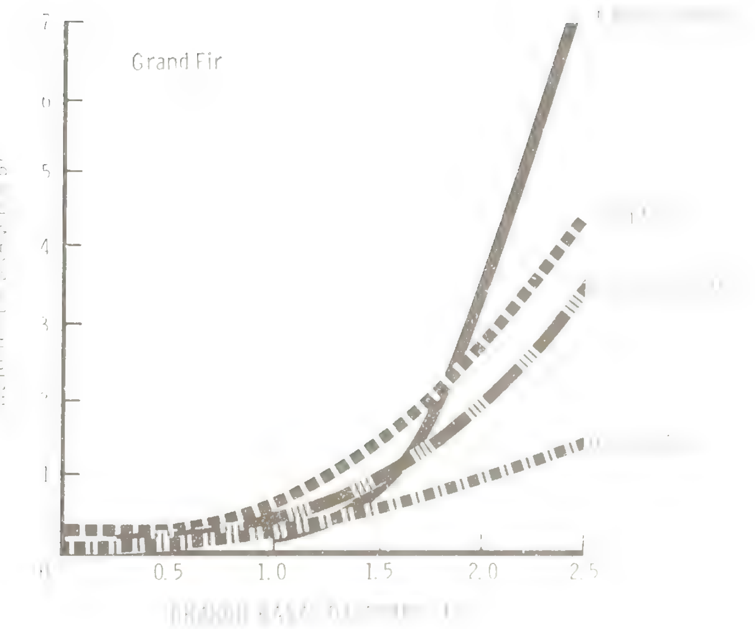
Foliage weight per branch related closely to species tolerance with the most tolerant species supporting the most foliage (fig. 10). For the species groups in figure 10, deviations in foliage weight between individual species and the group average were mostly less than 10 percent of the group average. The maximum deviation was a negative 25 percent for western white pine.

Foliage and Branchwood Fractions

For each species, five or six equations were required to describe the accumulative fractions of live and dead crown components. Most equations were exponential, and for live crown weight they provided close-fitting relationships between accumulative crown fractions and d.b.h. (fig. 11). Because of variation in retention of dead branchwood, accumulative fractions of dead crown components were less closely correlated with d.b.h. than accumulative fractions of live crown components. Equations for accumulative crown fractions and conditions for maintaining reasonable solutions at limits of the data are in appendix III.

Table 8.--[illegible]

[illegible]	-1.412		
[illegible]			.91
[illegible]	[illegible]		1.863
n	[illegible]		18
[illegible]	[illegible]		
r			.86
[illegible]	-2.457		6.091
n	9		
r	.12	.79	.70



ue 9.--Weight per branch
f foliage and branchwood
y size class as a function
f branch basal diameter
 grand fir.

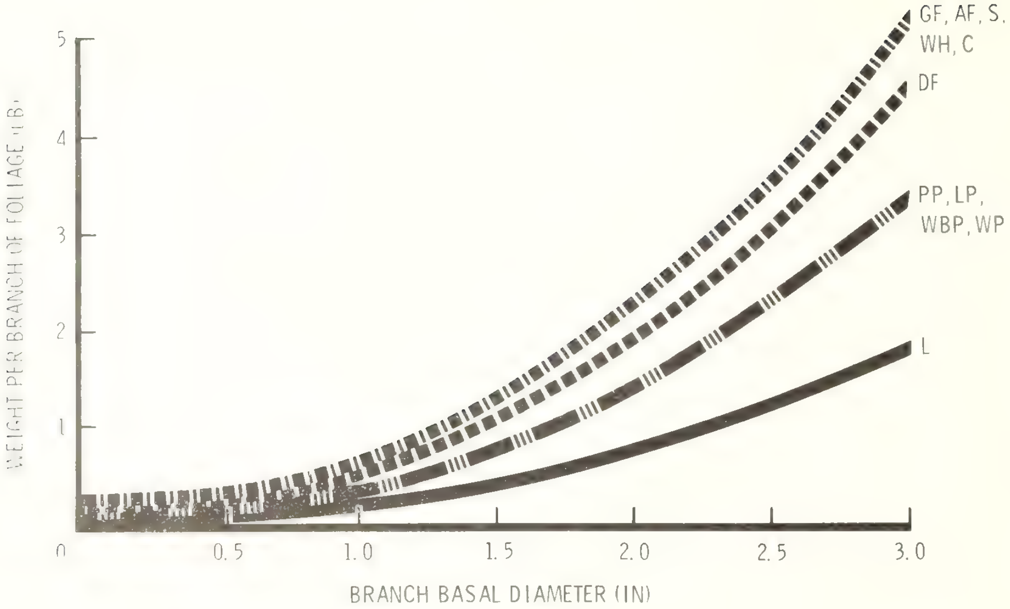


Figure 10.--Foliage weight per branch for groups of species that reflect general levels of species tolerance. Group 1 is the most tolerant and group 4 the least tolerant.

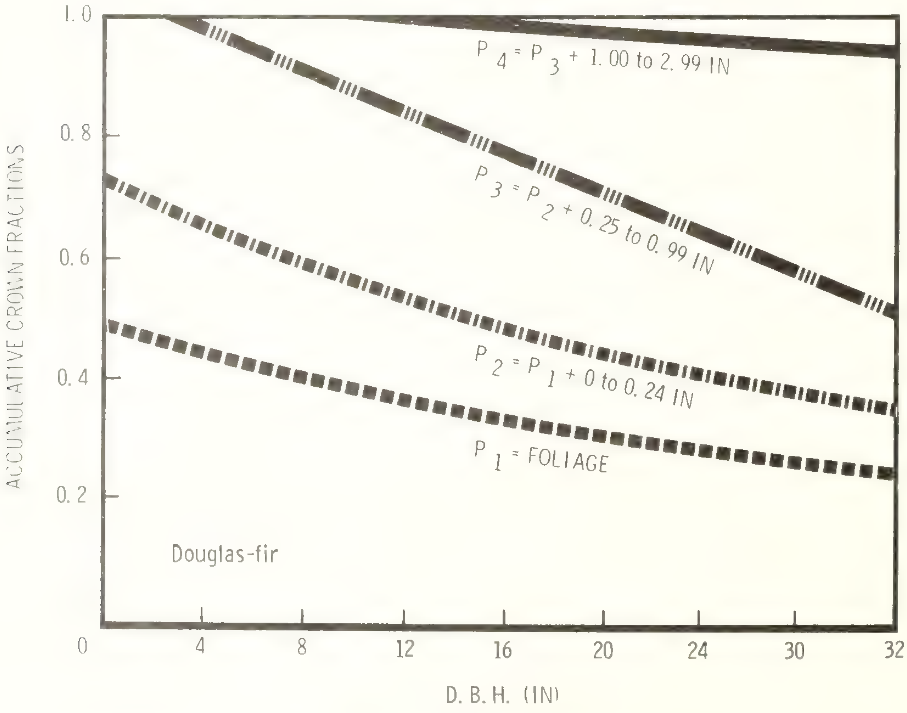


Figure 11.--Accumulative fractions of crown components for live crowns of Douglas-fir. For P_1, P_2, and P_3, $r^2 = 0.95$ and for P_4, $r^2 = 0.43$.

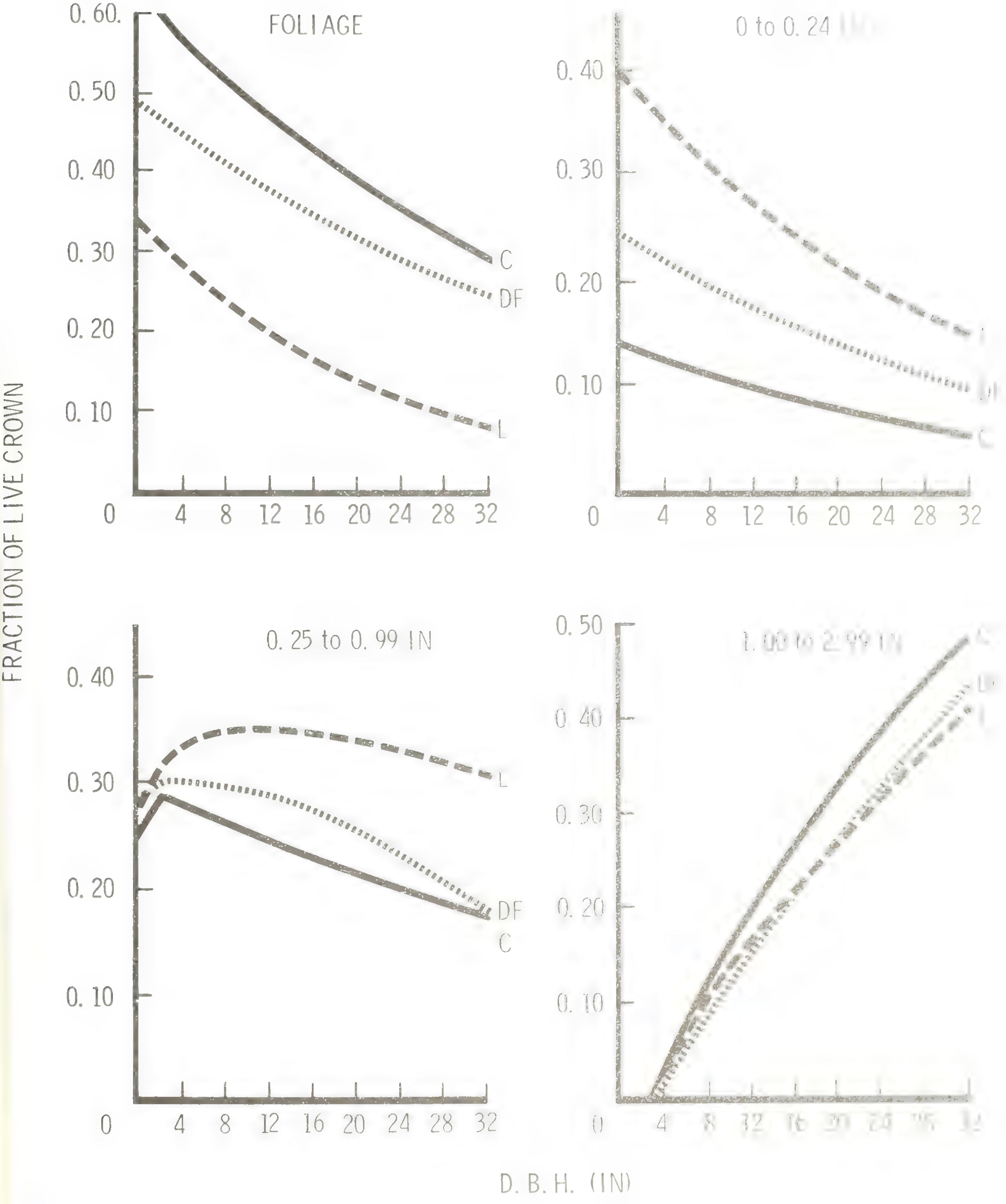

FRACTION OF LIVE CROWN
FOLIAGE
0.60
0.50
0.40
0.30
0.20
0.10
0
4
8
12
16
20
24
28
32
C
DF
L
0 to 0.24 IN
0.40
0.30
0.20
0.10
0
4
8
12
16
20
24
28
32
L
DF
C
0.25 to 0.99 IN
0.40
0.30
0.20
0.10
0
4
8
12
16
20
24
28
32
L
DF
C
1.00 to 2.99 IN
0.50
0.40
0.30
0.20
0.10
0
4
8
12
16
20
24
28
32
C
DF
L
D.B.H. (IN)

Figure [illegible].--[illegible]

Relationships between d.b.h. and actual fractions of foliage and branchwood components follow similar trends among species, probably largely influenced by the mechanical requirements for supporting suspended loads (McMahon 1975) (fig. 12). Foliage and 0- to 0.24-inch branchwood fractions decrease markedly with increasing d.b.h. The 0.25- to 0.99-inch branchwood fractions display the greatest variation; however, they generally increase up to 4 to 12 inches then decrease. The 1.00- to 2.99-inch branchwood fractions increase steeply throughout the range of sample tree data except for ponderosa pine. Its fraction levels off above a d.b.h. of 20 inches because increasing amounts of branchwood exceed 3 inches in diameter.

Large fractions of foliage and branchwood components are not necessarily associated with large weights per tree of foliage and branchwood components. The crown weights and component fractions must be viewed together to determine component weights. Generally, the tolerant species support the greatest weights of foliage, an exception being ponderosa pine which produces nearly as much foliage as Engelmann spruce at comparable tree diameters. Weights of 0- to 0.24-inch branchwood are greatest for the firs and hemlock. Weights of branchwood exceeding 1 inch are considerably greater for ponderosa pine than for other species.

For the species where dominants and intermediates were both sampled, the fraction of foliage for the dominants was consistently greater than for the intermediates, averaging 3 percentage points more at 2 inches d.b.h. and 16 percentage points more at 12 inches d.b.h. Differences in branchwood fractions between dominants and intermediates varied by species and d.b.h.; thus, any pattern of differences common to all species was not evident.

Bolewood Fractions

Weights of unmerchantable tips and boles of trees 4 inches and less in d.b.h. can be partitioned into 0- to 1-inch, 1- to 3-inch, and 3+-inch diameter size classes using fractions in table 9. Because unmerchantable tip and small tree bole material 0 to 0.25 inch in diameter was insignificant, this size class was lumped into the 0- to 1-inch class. The size class fractions are averages of data for all species. They were averaged after finding that variation of the fractions among species and dominants and intermediates was small.

Table 9.--*Fractions for partitioning weights of unmerchantable tips (for trees 5 inches and greater d.b.h.) and small tree boles (4 inches and less d.b.h.) into 0- to 1-inch, 1- to 3-inch, and 3+-inch size classes*

Size class (inch)	Tips			Small tree boles			
	Merchantable top diameter, inches			D.b.h., inches			
	3	4	6	1	2	3	4
0 - 1	0.03	0.01	0.003	0.08	0.03	0.01	0.01
1 - 3	.97	.39	.10	.91	.83	.31	.19
3+	0	.60	.90	.01	.14	.68	.80

Validation of Predictions

Verification of prediction equations [illegible] ariation in inventorying standing trees and [illegible] re difficult to control. Nonetheless, predictions were compared against inventoried eights in three stands dominated by a single species--ponderosa pine, Douglas-fir, and odgepole pine. Crown and bole weights were predicted before cutting from complete tand inventories on areas approximately 0.15 acre in size. D.b.h., crown ratio, and rown class were used in the predictions. After cutting, the fresh slash was intenively inventoried using the planar intersect method (Brown and Roussopoulos 1974).

For slash less than 3 inches in diameter, predicted weights were less than in entoried weights by 15, 22, and 37 percent of inventoried values. For all slash, redicted weights varied from 4 percent more to 15 percent less than inventoried eights. Some of the discrepancies were traced to biases in the test; thus, differnces between predicted weights and actual weights would be less than indicated by our est. The work in conducting a field verification test and the inconclusiveness of omparing two estimates based on sources of variation that are difficult to control kes this type of verification unappealing. The most productive verification would additional crown weight sampling.

Considering the standard errors of estimate for the crown and bole weight equations d the verification test, most estimates of slash weight from crowns and unmerchantable le tips for a stand of trees should be within 20 percent of the true mean. Occasionly estimates can be expected to deviate from the true mean by as much as 50 percent.

Crown Bulk Density

Bulk density of live crowns influences crown fire potential, interception of rain ll, interception of forest fire retardants, infrared detection of forest fires, and her phenomena. Quantifying bulk densities should help understand how tree species fect these phenomena and assist in analytical modeling of tree crown influences.

For dominants, bulk densities for foliage and all branches of live crowns ranged om 0.04 to 0.14 lb per cubic foot (fig. 13). The lowest bulk densities were displayed western redcedar and western larch, probably largely because of the open crown nature these species (Harlow and Harrar 1950). Crowns of whitebark pine had the greatest lk densities, probably because the sample trees were relatively old and slow grown, d possessed short thick branches. Subalpine fir and Engelmann spruce also had high lk densities, probably because branches were densely distributed within narrow crowns.

Bulk densities for foliage of live crowns averaged one-half of the bulk densities entire crowns (foliage and branchwood). The ratios of foliage bulk density to tire crown bulk densities ranged from 0.36 for ponderosa pine to 0.61 for Engelmann spruce. Species having high crown bulk densities also had high foliage bulk densities. Conversely, species having low crown bulk densities also had low foliage bulk densities.

Bulk densities for foliage computed using crown volumes, excluding foliage-free caities, differed only slightly from bulk densities based on crown volumes including foiage-free cavities. Because foliage-free cavities were a small part of crown voumes, only bulk densities based on the entire live crown volume are presented here. oiage-free cavities of the pines and larch, which are generally more intolerant and retain foliage for only 1 to 3 years, were larger than cavities of the other species.

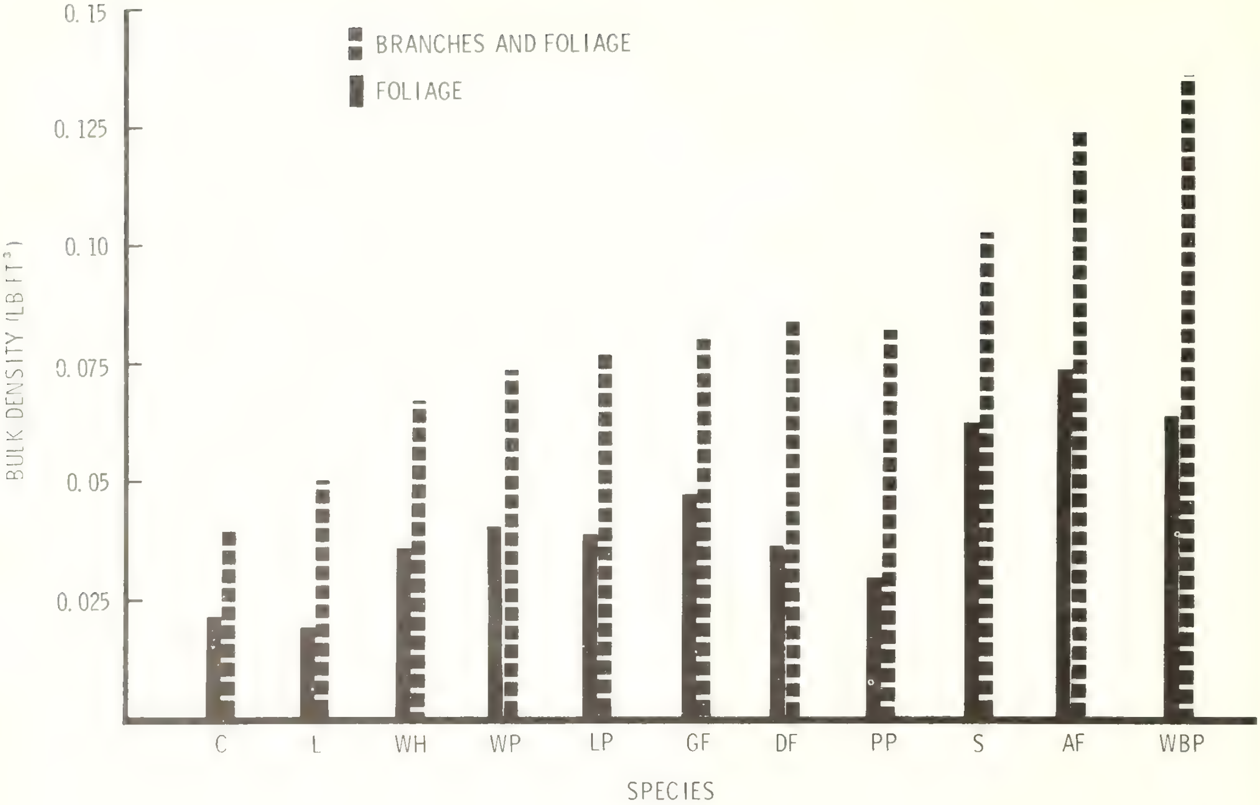
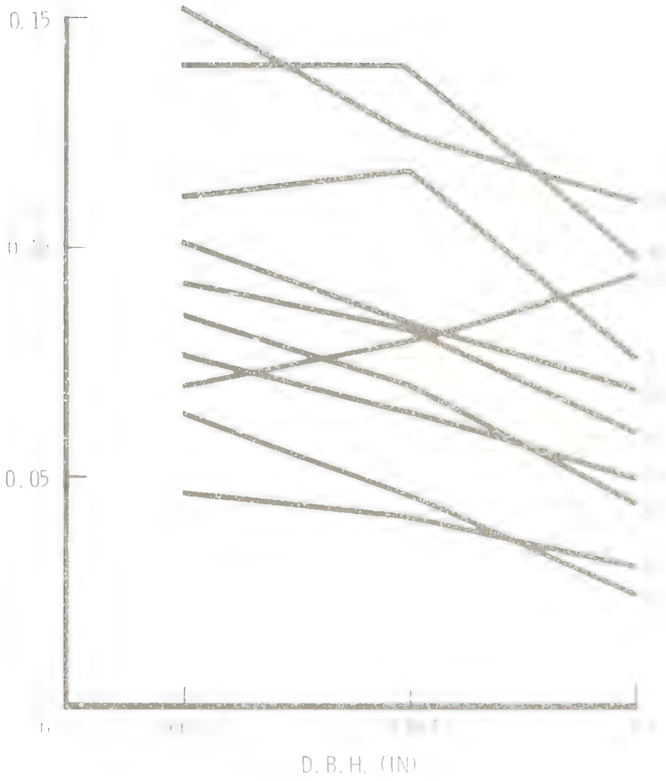


Figure 13.--Live crown bulk densities of dominants for foliage and for foliage and branchwood together. For all species, coefficients of variation for bulk densities of foliage and branchwood ranged from 32 to 65 percent, and averaged 47 percent.

Hence, bulk densities were altered more by omission of foliage-free cavities, as shown by the average ratios of bulk densities including foliage-free cavities to those without foliage-free cavities:

Species	*Ratios*
L, WP, PP, LP, WBP	1.16
AF, GF, DF, WH, C, S	1.03

To investigate the relationship between bulk density and d.b.h., regression analysis using polynomial, exponential, and linear models was employed. Relationships for only three species were significant and of these, the highest r^2 was 0.33. Although regression analyses failed to confirm relationships between bulk density and d.b.h., a plot of bulk density over averages of d.b.h. groups indicates that bulk density decreases as d.b.h. increases, at least up to 4 inches d.b.h. (fig. 14). One exception was ponderosa pine where bulk density increased with increasing d.b.h. Sample ponderosa pines of large d.b.h. were primarily from poor-to-medium sites. They supported many heavy branches, 3 to 6 inches in diameter, that probably accounted for the increased bulk density at large d.b.h.



Bulk densities increased vertically through the [illegible]
bulation of live crown bulk densities:

Species group	Crown section		Ratio of top-to-middle and bottom
	Top	Middle and bottom	
	(Pounds per cubic foot)		
DF, GF, WF, PP, LP	[illegible]	0.075	[illegible]
AF, WBP	[illegible]	.110	2.0
C, L	[illegible]	.042	[illegible]
S	114	.102	1.1
WH	.072	.068	1.1

Bulk densities of each species in a group were within 10 percent of the group aver-
g. Engelmann spruce and western hemlock showed little variation in bulk densities etween the upper and lower portions of the crown. Most of these sample trees had small .h. The data for the other tolerant species indicate that variation in bulk density etween upper and lower crown sections is greater for large trees. Thus, larger spruce n hemlock than studied here may show greater vertical variation in bulk density.

Bulk density of intermediates was less than for dominants but only decidedly so for rad fir, as shown in the following tabulation of intermediate-to-dominant bulk density atios:

Species	Intermediates-to-dominants ratios	
	Foliage and branches	Foliage
DF	0.80 (0.20)	0.81 (NS)
PP	.87 (NS)	[illegible]
C	[illegible]	.92 (NS)
GF	.66 (0.02)	[illegible]

The parentheses contain levels of significance from a two-tailed t-test of differences between the bulk densities for intermediates and dominants. Branches of the sample grand fir intermediates appeared normal in length but were more spindly and sparsely distributed than for dominants. Hence, crown volume of intermediates was large relative to weight, resulting in low bulk densities. Surprisingly, bulk densities of intermediates and dominants for ponderosa pine were not significantly different. Apparently, both crown weight and volume are reduced for intermediate ponderosa pine, resulting in little change in bulk densities. This seems likely to hold true for other species as well.

Moisture Content

Moisture contents were intensively sampled to determine ovendry crown weights. Thus, reliable moisture estimates of foliage and branchwood at top, middle, and bottom live crown positions were obtained. Coefficients of variation computed for each species using individual tree moistures averaged 16 percent for foliage and 18 percent for branchwood. Evaluation of differences in moisture content among species and of seasonal variation in moisture content was confounded by uncontrolled sources of variation and thus was not attempted.

At the same crown positions, foliage moisture was consistently greater than branchwood moisture by an average of 24 percentage points (table 10). Moisture contents of both foliage and branchwood were highest in the top sections and decreased downward through the crown. Perhaps the upper sections of tree crowns contain a larger proportion of young growth that is characterized by low dry matter content and high percentage moisture content than the lower sections of crowns. Or perhaps growing tips, distributed more densely in the upper sections, exercise priority in the distribution of water in response to internal water deficits (Kramer and Kozlowski 1960). In either case, higher moisture contents are maintained in the upper crown. The moisture content of entire live crowns averaged 102 percent for dominants and 86 percent for intermediates. Thus, simply doubling ovendry weights of crown material should result in reasonable estimates of fresh green weights.

Although the data clearly indicate that the moisture content of dominants is greater than intermediates, conclusions are tenuous because influences such as date and site confound the data for this comparison. Differences in moistures between crown sections of intermediates are much less than for dominants. In fact, foliage moistures of intermediates appear uniform throughout the crown.

The variation in moistures between foliage and branchwood and by crown position points out the need to select samples wisely when studying tree crown moisture contents in order to avoid bias.

This study has provided equations based on about 500 sample trees for predicting weights of foliage, live and dead branchwood, and small tree boles. Relationships between tree crown biomass and d.b.h., tree height, crown length, crown ratio, and crown class were evaluated in selecting the most precise and useful equations. Tree crown bulk densities were also determined. This information provides a basis for appraising fire behavior potential of tree cutting activities in advance of cutting. Numerous other applications from predicting tree crown biomass are also possible.

Table 10. [illegible]

Fuel component	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Foliage	116	111	[illegible]	[illegible]	[illegible]	[illegible]
Branchwood:						
0 to 0.25 inch	100	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.25 to 1 inch	[illegible]	[illegible]	[illegible]	[illegible]	74	[illegible]
1 to 3 inches	[illegible]	[illegible]	74	[illegible]	71	[illegible]
All components	111	[illegible]	[illegible]	[illegible]	84	[illegible]

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APPENDIX I

Geographic Distribution of Sample Trees

Location of sample trees is presented [illegible] bine data of their own with data from this study (fig. 15 and table 11).

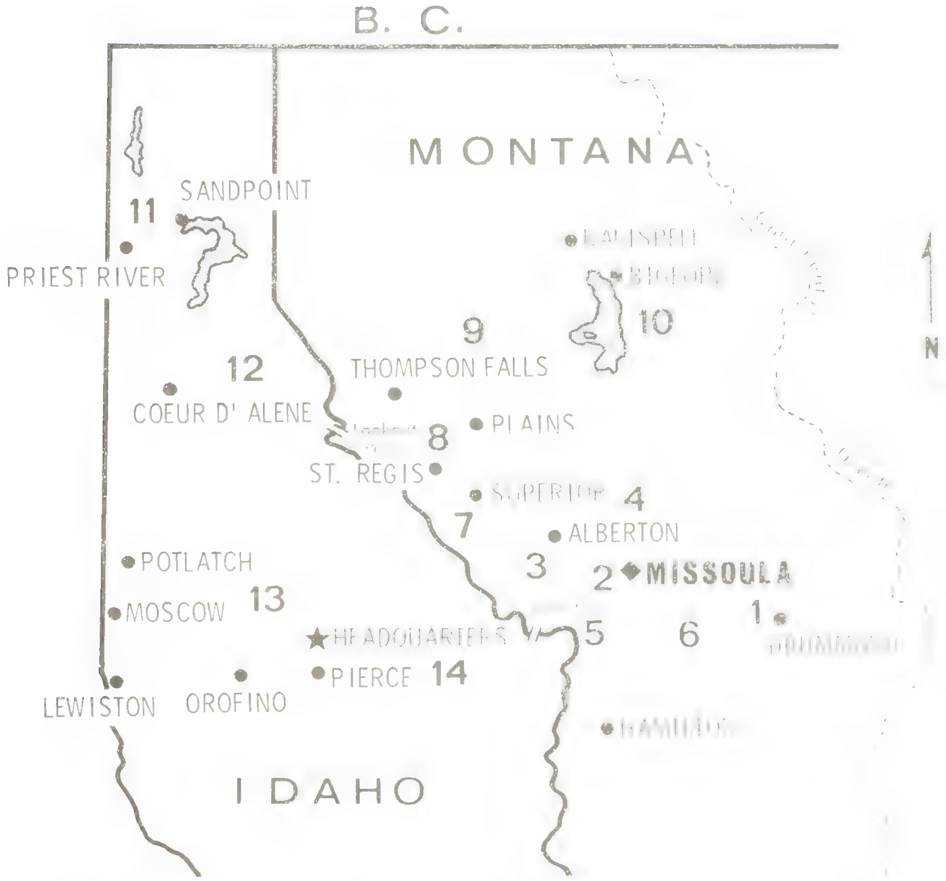

Figure 15.--[illegible] *the map are identif*[illegible]

Table 11.--Location of individual sample trees by species. The 800 series designates intermediates; others are dominants

No.	Area	Identifying tree numbers										
		PP	WP	LP	WBP	AF	DF	GF	C	L	WH	S
1	Bearmouth	1-7										
2	Missoula	8-15, 19			192-197, 225-233, 237,C40- C42	236	801, 802					
3	Fish Creek	16-18,124, 126, 821		21,22,24, 25		147,149, 151,152, 200,201, 203	20,23,26, 27,125,184, 822,853, 858,860, 873	834,835, 838,866, 872	817-820, 836,837			148,150, 202
4	Ninemile	129,154, 155,211, 212,811, 813,814, 816,843, 854,855	C30	84,87,88, 90,91		86,188, 189,223	95-98,123, 130,166, 210,C32, 803,812, 815,856, 857	153,222, 224,832, 833,844, 863	156,157, 187,C28, C29,830, 831,862, 864,865, 874,875	82,83,89, 92-94		85,165, C25,C26, C27,C31
5	Lolo Creek					127				99,100,128		101,102
6	Swartz Creek					217	804-806, 828,829					219
7	Superior	45,115,122, 199,845-852, 868	28,29,158	38		31,34,47, 159,161	36,41,48, 208,209, 861,881	42,43,825, 827,867	37,39,40, 44,46,823, 824,826, 879,880			30,32,33, 35,160
8	St. Regis	876-878, 884	52,79,163, C33			51,78,164, 215	53,54,840, 869,871	162,186, 218,807, 810,841, 842,870, 882,883, 887	49,50,77, 185,191, 214,808, 809,839	80,81		190,213
9	Plains	121,198	216,C34- C36,C37	C18-C24		234,235	118, 204-206	116,117, 207,C16, C17,885, 886		119,120		C38,C39
10	Big Fork		144					141,142, 146	131,132, 136,138- 140,859	133-135, 137,143, C01-C07		145
11	Priest River Exp. Forest						C43,C49	238, C44-C47	C48			
12	Deception Creek		177				183				167-176, 178-182, C08-C15	
13	Moscow	57,58,70	55,59,60, 72,73,221	75,76				56,61,62, 64,67,71	74 ,220		63,65,66, 68,69	
14	**Pierce**		104,105, 109,112, 113					108,114	106,107, 110,111			103

APPENDIX II

Listing of Data

Raw data for dominants are in table 12 and for intermediates in table 13. [illegible] es, tree numbers with a prefix C designate sample trees for which live crown weight not measured. A dash in a column of data means no data taken.

Data from Fahnestock (1960) and Storey and others (1955) that were used in formulat live crown weight equations are not listed. However, the d.b.h. distribution of r sample trees is shown in table 14.

Table 12.--*Raw data for dominants*

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight					Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
								Foliage	Branchwood (inches)										
									0 to 0.25	0.25 to 1	1 to 3	3+							
	Inches	*Ft*	*Yr*	*Ft*	*Ft*	*Inches*	*Lb*	*Lb*					*Lb*	*Ft*	*Inches*	*Ft³*		*Ft²*	
DOUGLAS-FIR																			
27	0	4.2	17	4.2	2.9	--	0.0088	0.6812	0.3616	0.3307	0	0	0.18	4.2	2	11.93	1	81	646
96	0	4.5	8	4.5	2.2	1.3	0	.5181	.2822	.1455	0	0	.37	4.5	2	7.86	1	17	900
98	0	4.5	8	3.9	2.5	.9	.0022	.2028	.1124	.0419	0	0	.28	4.5	1	7.12	1	11	7,200
183	0	3.7	6	3.7	2.5	.9	0	.2800	.1587	0	0	0	.19	3.7	1	7.97	3	7	1,100
34	0.4	6.8	10	6.8	4.2	2.2	.0176	2.011	1.045	1.230	0	0	1.12	6.8	3	27.57	2	23	1,812
23	.5	5.8	25	4.7	4.0	--	.0309	1.340	.6967	.8113	0	0	1.31	5.8	2	19.17	1	2	1,200
36	.5	6.2	10	6.2	3.6	1.8	.0022	.8466	.4034	.4145	0	0	.75	6.2	2	27.26	4	15	3,100
20	.7	7.1	18	5.5	4.3	--	.0044	1.645	.8532	.9304	0	0	1.91	7.1	3	51.8	1	41	557
95	1.0	9.4	12	9.1	4.8	2.6	0	2.511	1.270	1.660	0	0	2.69	9.4	3	67.57	3	3	900
125	1.2	9.1	10	8.6	4.2	2.4	.0220	2.079	1.085	1.111	0	0	2.42	9.1	3	36.5	3	6	3,600
130	1.9	11.4	15	11.4	6.7	4.0	.0022	5.752	2.870	3.743	0	0	6.36	11.3	1	157.2	3	3	900
26	2.2	14.4	30	11.1	6.0	--	.2557	3.827	1.938	2.456	0	0	8.92	11.4	1	151.0	2	51	900
97	2.2	11.4	12	10.6	4.9	3.2	0	4.374	2.216	2.932	0	0	7.02	11.4	4	87.4	4	47	1,800
53	2.4	14.1	22	13.1	7.5	3.5	.0904	7.196	3.572	5.324	0	0	10.2	14.1	1	281.1	1	42	900
123	2.5	14.1	14	14.1	6.2	4.8	.0041	10.44	5.095	7.639	0	0	11.6	14.1	6	130.3	3	15	300
184	3.2	20.1	25	15.9	6.2	3.2	.6438	1.799	.9193	1.160	0	0	16.8	20.1	6	251.7	3	103	3,931
166	5.7	34.1	88	25.1	8.2	5.3	4.090	16.71	8.175	12.42	0	0	67.2	30.8	6	538.8	1	101	664
118	7.5	44.6	71	24.2	9.8	5.6	9.469	25.67	12.09	19.38	1.523	0	62.9	28.6	6	1,311	2	115	511
206	9.8	58.9	85	29.9	19.3	6.7	37.33	46.18	21.49	34.78	11.19	0	51.8	25.7	6	2,722	3	75	555
41	10.7	67.9	75	30.3	10.1	6.8	22.33	35.43	16.34	26.79	13.24	0	50.5	24.9	6	1,021	1	220	555
C49	12.1	74.3	63	56.0	16.9	10.2	34.94	--	--	--	--	--	--	--	6	3,328	6	100	306
C43	13.1	70.2	114	52.8	17.2	10.5	31.44	--	--	--	--	--	--	--	6	6,921	4	180	522
C32	17.9	111.1	111	52.3	11.7	10.8	14.69	--	--	--	--	--	--	--	6	3,047	7	221	742
204	21.6	92.0	203	53.4	19.2	15.5	119.8	162.6	68.71	126.6	198.2	0	30.8	15.3	6	9,042	5	160	150
48	25.0	106.3	181	61.8	28.0	17.2	173.6	210.3	87.69	164.5	287.6	9.006	34.0	17.7	6	11,948	6	204	3,060
205	26.4	92.3	210	63.8	20.2	18.8	181.6	170.6	69.99	133.8	263.9	30.10	26.9	13.4	6	11,709	5	55	513
208	28.3	142.7	219	81.7	20.1	18.3	220.6	255.2	108.2	199.0	304.6	0	43.0	20.9	6	6,860	7	238	997
210	30.5	112.9	210	85.9	21.4	23.9	196.5	336.3	135.4	264.6	595.8	114.0	29.6	15.2	6	15,263	6	60	21
209	33.9	136.0	262	70.8	29.9	20.3	531.1	238.9	99.01	187.0	346.8	27.28	38.8	19.8	6	29,031	7	140	46

(con.)

Table 1. [illegible]

[illegible] height [illegible] crown [illegible] width [illegible] weight

Live crown weight

Branchwood [illegible]

[illegible]

Table 12.--(con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Foliage	Live crown weight: Branchwood (inches) 0 to 0.25	0.25 to 1	1 to 3	3+	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	Lb	Lb	Lb	Lb	Lb	Lb	Ft	Inches	Ft³		Ft²	
								GRAND FIR											
15	0	4.6	8	4.6	2.0	1.0	0.0022	0.4762	0.2138	0	0	0	0.25	4.5	1	10.37	1	2	[illegible]
61	0	4.4	7	4.4	3.5	1.4	0	1.157	.4740	0.2668	0	0	.67	4.4	2	24.46	1	1	300
62	0	3.7	6	3.7	1.9	1.0	0	.4519	.2050	0	0	0	.19	3.7	1	4.43	1	1	[illegible]
114	0	3.1	4	3.1	2.1	.9	0	.3461	.1565	0	0	0	.19	3.1	1	[illegible]	[illegible]	1	[illegible]
67	0.4	5.7	9	5.7	3.2	1.7	.0022	.9149	.3924	.1213	0	0	.64	5.7	2	13.08	1	1	[illegible]
71	.4	5.5	8	5.0	3.3	1.6	0	1.199	.4806	.3329	0	0	.89	5.5	2	[illegible]	2	1	[illegible]
141	.7	7.0	10	7.0	3.9	1.5	0	1.071	.4431	.2359	0	0	.88	7.0	2	25.47	[illegible]	10	[illegible]
162	1.0	9.5	17	8.1	5.7	1.6	.0617	1.347	.5534	.2998	0	0	1.40	9.5	2	35.64	3	[illegible]	[illegible]
42	1.1	7.6	42	6.6	4.4	2.2	.0022	4.228	1.682	1.272	0	0	1.68	7.6	3	42.83	1	3	[illegible]
153	1.1	8.9	8	7.9	5.1	2.2	0	4.023	1.609	1.131	0	0	2.37	8.9	3	67.17	3	2	[illegible]
142	1.5	9.5	10	9.0	5.9	2.0	.0331	2.672	1.096	.6217	0	0	2.22	9.5	3	71.47	3	11	[illegible]
64	1.8	14.0	12	11.6	5.2	2.2	.1698	2.985	1.186	.8885	0	0	4.11	14.0	3	88.88	1	19	[illegible]
146	2.1	12.3	12	12.3	5.3	4.1	.0088	9.449	3.620	3.393	0	0	6.05	12.3	6	128.8	3	13	[illegible]
108	2.3	14.3	18	12.3	5.2	2.6	.0882	5.479	1.261	1.515	0	0	6.84	11.3	3	111.7	3	112	[illegible]
186	2.7	16.0	35	11.2	9.0	2.5	.2491	5.075	1.927	1.900	0.3483	0	9.72	16.0	4	214.2	1	220	2,427
56	3.2	18.5	23	17.0	6.5	3.9	.2271	10.20	3.867	3.810	0	0	11.6	18.5	6	227.8	3	24	2,100
220	4.2	22.1	30	20.9	10.5	5.1	1.360	21.62	8.054	8.719	0	0	31.0	22.1	6	617.0	4	94	2,700
222	4.3	22.4	22	20.4	7.2	5.1	.3549	25.70	9.643	10.12	0	0	29.6	22.4	6	292.8	6	11	300
238	6.5	40.6	32	38.6	14.3	6.7	2.262	41.73	15.13	19.14	5.972	0	54.1	34.1	6	2,011	6	120	300
218	7.5	47.5	124	41.6	10.3	7.4	9.614	33.09	12.23	14.03	3.503	0	57.0	29.7	6	1,882	1	180	7,079
207	10.5	78.8	93	69.6	13.3	10.4	35.57	101.6	35.32	54.97	40.99	0	58.5	25.5	6	4,165	1	115	132
221	11.9	79.0	121	67.0	13.8	11.5	46.40	77.09	27.05	40.42	29.36	0	33.2	20.7	6	1,195	1	201	571
C17	12.3	71.5	85	55.0	16.8	10.7	53.54	--	--	--	--	--	--	--	6	2,246	1	180	304
116	12.4	69.0	91	40.7	15.5	10.0	46.13	73.03	25.42	39.38	29.18	0	29.8	17.5	6	3,548	2	176	866
C16	13.6	69.1	85	53.1	17.5	11.8	69.38	--	--	--	--	--	--	--	6	2,253	1	100	96
117	15.6	72.7	92	47.7	21.9	13.5	104.3	181.8	61.52	108.9	115.3	0	20.1	12.2	6	9,585	1	132	1,664
C44	16.0	103.8	81	55.1	19.5	11.3	90.13	--	--	--	--	--	--	--	6	4,644	1	300	340
C47	18.8	131.4	91	68.5	12.5	12.7	10.16	--	--	--	--	--	--	--	6	6,217	6	140	676
C46	19.0	126.3	96	94.3	22.8	16.6	89.49	--	--	--	--	--	--	--	6	10,028	5	189	901
C45	20.4	136.8	106	108.1	17.3	17.0	200.1	--	--	--	--	--	--	--	6	13,859	5	124	737

Table 12.--Con.

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight: Foliage	Branchwood 0 to 0.25 in.	0.25 to 1	1 to 3	3+	Bole top weight	Bole top length	Bole top dia.	Crown volume	[illegible]	Tree [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 12.--Con.

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
								Foliage	Branchwood (in.)										
									0 to 0.25	0.25 to 1	1 to 3	3+							
							[illegible]	Lb											
								PONDEROSA PINE											
[illegible]	[illegible]	1.7	[illegible]	4.[illegible]	[illegible]	--	0	0.5515	0.1146	0.3171	0	[illegible]	1.3	[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]
[illegible]	[illegible]	1.5	7	[illegible]	5.3	-	0	.5445	.1036	.3305	0	[illegible]	.15	1.[illegible]	[illegible]	[illegible]	1	[illegible]	2[illegible]
[illegible]	[illegible]	2.3	7	2.5	1.6	--	0.0067	.1852	.0529	.0838	0	0	.18	2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	1.6	6	[illegible]	2.1	--	.0132	.2624	.0705	.1270	0	[illegible]	.58	1[illegible]	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.4	5.5	7	5.0	4.1	1.0	.0088	1.038	.1808	.6947	0	[illegible]	1.22	[illegible].5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.7	6.[illegible]	[illegible]	[illegible]	3.8	1.8	0	.7251	.1477	.4131	0	[illegible]	1.32	[illegible]	2	24.[illegible]	[illegible]	[illegible]	[illegible]
134	.7	[illegible].7	6	4.5	3.3	1.1	.0573	.5762	.0791	.2271	0	[illegible]	.91	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
126	.8	6.1	11	4.8	4.1	2.1	.0595	1.380	.2844	.5378	0	[illegible]	1.84	[illegible]	[illegible]	[illegible]	1	17	[illegible]
29	1.0	5.9	20	5.9	3.9	--	.0287	2.831	1.109	0	0	[illegible]	3.25	5.[illegible]	3	[illegible]	[illegible]	[illegible]	[illegible]
57	1.5	9.7	6	9.2	4.0	2.2	.0154	1.034	.1545	.7408	0	[illegible]	2.95	[illegible]	3	[illegible]	[illegible]	17	[illegible]
129	1.[illegible]	7.8	11	6.8	3.4	2.[illegible]	.0110	2.244	.3329	1.612	0	0	2.79	7.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1[illegible]	1.9	10.0	20	7.0	5.4	--	.2579	2.410	.3020	1.861	0	[illegible]	1.29	10.0	[illegible]	[illegible]	[illegible]	37	[illegible]
16	2.6	11.0	18	[illegible].5	6.4	--	.2579	6.378	.7341	5.121	0	0	8.78	10.[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]
17	3.2	15.3	25	10.[illegible]	[illegible]	--	.5930	3.605	.4938	2.701	0	0	10.56	17.3	4	[illegible]	[illegible]	[illegible]	[illegible]
58	3.2	13.9	7	13.[illegible]	7.1	4.8	0	5.472	.4916	4.[illegible]85	2.[illegible]	[illegible]	14.18	[illegible]	[illegible]	17.[illegible]	[illegible]	[illegible]	[illegible]
124	3.7	13.9	1[illegible]	11.6	6.0	4.0	.3638	8.944	.9158	7.454	1.2[illegible]	0	14.78	1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	4.4	28.3	15	19.8	5.4	--	3.682	6.435	.7893	5.077	.6856	0	20.78	[illegible]	4	[illegible]5	[illegible]	[illegible]	[illegible]
11	6.4	37.6	59	22.2	7.5		6.964	11.45	1.019	10.25	1.129		12.52	[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]
45	7.6	38.8	36	28.9	10.1	7.6	8.792	25.69	1.925	24.82	19.54	0	10.15	15.[illegible]	[illegible]	1,[illegible]	[illegible]	[illegible]	[illegible]
8	7.8	40.9	45	28.4	11.3	--	20.41	25.47	1.808	25.24	21.95	0	9.73	12.4	4	1,47[illegible]	[illegible]	1[illegible]	3
9	10.5	50.6	57	30.1	12.9		36.63	39.82	2.070	45.23	14.07	0	8.50	11.2	4	1,[illegible]7	[illegible]	[illegible]	[illegible]5
122	11.2	71.3	78	40.3	11.0	8.7	35.85	47.96	3.031	50.10	16.17	0	40.88	22.7	6	2,3[illegible]	1	18	[illegible]
211	11.3	66.6	85	32.3	8.3	7.3	47.42	28.18	2.150	27.28	21.89	0	13.37	22.5	6	1,157	[illegible]	60	[illegible]
115	13.8	72.1	81	38.9	17.9	9.8	118.4	84.56	4.780	92.68	88.24	0	14.52	22.4	6	4,111	3	2[illegible]	[illegible]
212	14.2	72.4	87	56.1	18.0	12.4	7.227	132.0	13.73	146.8	142.1	0	41.56	22.1	6	6,771	3	64	[illegible]
7	18.2	76.9	155	46.5	17.0	--	80.78	124.9	0	185.1	257.6	39.56	4.68	9.0	4	5,[illegible]	1	14	[illegible]
2	19.2	82.5	100	65.6	26.5	-	77.06	196.2	0	359.2	157.0	0	9.53	12.5	4	[illegible],698	3	21	[illegible]
199	20.6	85.5	72	66.5	26.7	17.0	260.9	266.6	9.749	352.8	366.1	161.8	55.06	19.1	6	13,1[illegible]	5	14	[illegible]
5	21.1	76.7	210	30.7	16.8		71.12	102.3	1.832	161.5	183.8	131.4	3.92	5.7	4	1,613	1	12	8
6	24.3	78.2	210	39.8	19.5	-	67.35	146.4	8.201	269.1	138.6	245.5	3.22	7.0	7	1,958	1	1[illegible]1	[illegible]
4	25.5	87.3	210	57.7	22.4	--	123.3	150.8	1.667	314.4	271.2	357.0	1.88	7.5	4	11,517	1	8[illegible]	[illegible]
3	28.3	78.4	210	52.7	31.1	-	373.0	163.7	1.737	295.1	267.5	813.2	6.01	8.9	4	20,307	1	[illegible]	1[illegible]
1	31.3	112.8	217	78.5	40.1	--	294.4	211.2	0	506.8	554.6	122.4	6.58	9.1	4	14,028	[illegible]	82	3[illegible]
121	31.5	121.0	181	89.2	34.7	26.4	259.6	407.4	11.97	588.8	626.5	583.0	27.70	16.5	6	32,77[illegible]	[illegible]	8[illegible]	[illegible]
198	34.0	144.4	192	85.9	29.6	24.8	52.57	501.0	14.69	735.4	783.4	875.1	9.72	16.5	6	30,500	5	10	[illegible]

Table 12 -- Con.

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight: Foliage	Live crown weight: Branchwood 0 to 0.5	[illegible]	[illegible]	Bole weight	Bark [illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 12.--(con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Foliage	Live crown weight, Branchwood (inches), 0 to 0.25	0.25 to 1	1 to 3	3+	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	Lb	Lb	Lb	Lb	Lb	Lb	Ft	Inches	Ft³		Ft²	
WESTERN HEMLOCK																			
68	0	4.4	10	3.9	2.2	1.6	0	0.3373	0.1808	0.0485	0	0	0.27	4.4	2	8.57	1	1	[illegible]
178	0	4.5	5	4.3	2.0	.6	0	.1080	.0595	0	0	0	.12	4.5	1	5.84	4	7	1,800
180	0	3.8	3	3.0	1.9	.5	0.0022	.0992	.0529	.0132	0	0	.09	3.8	1	3.79	2	7	3,200
181	0	3.6	4	3.6	1.4	.6	0	.0838	.0441	0	0	0	.09	3.6	1	2.54	3	2	1,500
175	0.1	6.5	7	5.5	2.2	1.0	0	.3175	.1698	.0309	0	0	.38	6.5	2	[illegible]	5	2	1,200
66	.2	5.9	8	5.9	2.7	1.5	0	.4321	.2315	.0728	0	0	.39	7.9	2	10.24	2	1	3,000
167	.3	8.6	7	7.2	3.2	1.1	0	.6945	.3748	.0750	0	0	.77	8.6	2	13.74	1	21	1,800
174	.6	8.3	6	7.7	4.1	1.7	0	.9700	.5159	.2998	0	0	.89	8.3	2	24.20	3	83	2,720
168	1.3	12.7	19	9.8	4.2	1.8	.0198	1.506	.7959	.5534	0	0	3.31	12.7	3	26.70	2	39	1,287
179	1.5	13.6	8	12.5	4.5	2.2	.0110	1.660	.8819	.5159	0	0	3.06	13.6	3	31.00	3	3	1,200
173	1.8	12.7	24	11.9	4.8	3.0	0	4.132	2.176	1.839	0	0	3.84	12.7	4	67.62	1	90	3,117
63	2.0	15.4	19	15.4	5.0	2.9	.0044	3.113	1.620	1.728	0	0	3.87	15.4	3	133.7	5	59	3,100
65	2.1	16.2	13	14.2	5.2	2.4	.0860	3.869	2.030	1.784	0	0	6.23	16.2	3	87.71	1	72	7,200
69	2.3	18.2	17	15.2	5.7	2.5	.0838	2.679	1.409	1.217	0	0	7.89	18.2	4	145.8	1	20	4,200
169	3.0	21.4	25	17.5	9.3	3.2	.0860	7.046	3.662	3.829	0	0	17.4	21.4	6	269.9	3	62	3,000
171	3.1	20.3	21	19.0	6.9	3.5	.0044	6.934	3.605	3.640	0	0	15.3	20.3	4	153.7	5	62	3,000
172	5.0	29.0	25	27.0	10.1	5.2	.0838	15.11	7.681	9.162	0.8488	0	42.5	29.0	6	718.9	7	128	1,026
170	5.7	27.4	23	25.6	10.7	6.2	.0838	20.95	10.76	13.17	0	0	12.8	24.3	6	784.1	3	85	1,286
176	6.3	35.2	23	35.2	12.3	7.0	1.157	32.09	16.44	20.81	4.799	0	43.1	27.3	6	1,261	5	148	6,039
182	7.0	38.4	32	38.4	12.8	7.2	.0882	31.46	16.12	20.21	2.967	0	47.5	29.4	6	1,610	3	129	848
C15	9.6	72.8	95	61.6	19.7	9.0	--	--	--	--	--	--	--	--	6	--	2	123	1,332
C13	10.3	78.2	108	62.7	15.8	9.5	--	--	--	--	--	--	--	--	6	--	1	320	436
C10	15.8	116.4	116	69.9	21.3	12.0	--	--	--	--	--	--	--	--	6	--	3	100	71
C 9	16.9	115.2	176	69.2	20.3	13.2	--	--	--	--	--	--	--	--	6	-	1	140	106
C 8	17.3	125.5	156	66.1	24.5	13.0	--	--	--	--	--	--	--	--	6	--	2	120	88
C12	18.9	115.3	121	76.8	31.5	16.4	--	--	--	--	--	--	--	--	6	--	3	100	83
C11	20.2	125.4	122	72.0	24.0	15.6	--	--	--	--	--	--	--	--	6	--	3	160	106
C14	21.4	126.2	161	111.5	31.6	21.1	--	--	--	--	--	--	--	--	6	--	3	180	88

(con.)

Table 12.--(con.)

Tree No.	d.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight					Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
								Foliage	Branchwood (inches)										
									0 to 0.25	0.25 to 1	1 to 3	3+							
								WESTERN LARCH											

Table 12.--con.

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Foliage	Live crown weight Branchwood (inches) 0 to 0.25	 0.25 to 1	 1 to 3	 3+	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area acre	Trees acre
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	-------	-------	Lb	-------	-------	Lb	Ft	Inches	Ft³		Ft²	
WESTERN REDCEDAR																			
57		1.8	6	1.8	1.1	1.1	0	0.0061	0.0061	0	0	0	0.02	1.8	2	1.33	1	3	2,100
111	[illegible]	5.6	7	5.6	2.9	0.9	0	.3505	.0882	0	0	0	.20	5.6	1	9.58	3	1	500
152	[illegible]	5.7	6	5.7	3.0	1.1	0	.3880	.0948	.0728	0	0	.18	5.7	2	8.78	1	7	3,100
151	0.1	5.4	7	5.4	3.3	1.4	0.0041	.6614	.1587	.1676	0	0	.31	5.4	2	19.30	2	2	1,200
158	.4	6.0	6	5.7	3.5	1.1	0	.3219	.0794	.0595	0	0	.36	6.0	2	18.18	6	11	7,800
41	.8	7.7	15	7.7	4.8	2.0	0	1.336	.3109	.5071	0	0	1.45	7.7	3	75.27	1	7	4,200
157	.8	8.2	10	8.2	5.9	2.0	.0463	1.041	.2403	.4586	0	0	1.39	8.2	3	45.80	3	4	3,000
187	.8	7.9	11	7.9	5.1	2.4	.0485	.8951	.2072	.3836	0	0	.91	7.9	3	68.02	1	3	1,800
40	1.5	9.9	20	9.9	6.7	3.7	.1631	3.391	.8267	1.735	0	0	3.29	9.9	4	148.8	1	3	900
146	1.5	10.1	52	5.9	5.5	1.6	.1499	1.854	.4299	.8532	0	0	3.13	10.1	3	55.54	1	8	3,600
150	1.8	12.6	19	12.6	7.2	3.0	0	4.264	.9524	2.061	0	0	5.10	12.6	3	120.3	3	4	600
59	2.0	11.8	13	11.8	8.4	3.4	0	3.609	1.237	2.820	0	0	4.81	11.8	4	238.7	3	15	300
74	2.1	16.2	16	13.2	5.1	2.4	.0616	3.609	.8201	1.768	0	0	6.13	16.2	4	144.3	3	51	1,811
110	3.4	19.9	17	19.9	10.9	6.6	0	12.97	2.822	6.713	0	0	18.1	19.9	6	817.9	3	71	1,500
159	3.6	21.1	31	13.1	8.3	3.3	.0904	7.778	1.706	3.968	0	0	20.3	21.1	6	233.4	1	34	2,400
46	3.7	20.1	27	20.1	8.5	5.5	.0838	14.39	3.150	7.368	0	0	22.5	20.0	6	614.1	2	36	3,900
49	4.2	24.3	48	18.9	8.0	4.0	.1742	13.27	2.908	6.801	0	0	34.5	24.3	6	517.3	1	81	4,620
156	6.1	30.0	150	23.9	11.2	3.8	4.861	11.09	2.381	5.807	1.142	0	81.0	38.7	6	1,144	1	120	307
214	8.0	44.2	80	38.0	17.8	7.9	2.996	41.11	8.719	21.59	10.35	0	35.2	28.6	6	3,148	1	148	6,227
77	10.6	67.6	84	51.5	15.8	8.9	16.62	52.99	11.30	27.85	12.51	0	55.0	30.0	6	4,249	3	241	1,417
28	12.6	66.2	99	45.3	16.0	9.7	16.01	--	--	--	--	--	--	--	6	4,094	3	140	154
48	15.5	77.0	76	68.1	20.3	13.9	29.58	--	--	--	--	--	--	--	6	6,339	5	300	354
29	17.6	77.9	106	56.4	22.6	13.2	40.43	--	--	--	--	--	--	--	6	9,235	3	200	186
50	18.6	101.1	171	80.8	19.3	15.2	78.19	137.8	28.27	75.15	97.43	0	40.4	22.2	6	8,037	3	220	110
185	21.0	105.2	237	76.0	26.0	16.4	108.0	154.6	31.40	85.07	138.5	0	45.2	24.3	6	17,831	1	236	728
107	22.9	117.2	216	98.2	30.4	18.8	156.6	249.4	50.16	147.2	264.2	0	33.2	18.3	6	33,742	4	246	4,603
191	26.3	107.3	210	84.3	24.1	21.4	178.5	212.9	42.58	118.8	284.6	9.275	33.5	21.6	6	17,068	1	202	646
106	26.6	126.3	210	80.2	25.0	19.3	195.1	226.2	45.53	125.5	237.1	0	29.5	16.2	6	14,383	4	240	401

(con.)

Table 12.--(con.)

Tree No.	d.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight: Foliage	Branchwood 0 to 0.25	0.25 to 1	1 to 3	3+	Bole weight	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 12.--(con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Foliage	Live crown weight Branchwood (inches) 0 to 0.25	 0.25 to 1	 1 to 3	 3+	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area acre	Trees acre
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	- - - - - -	- - - - - -	Lb	- - - - - -	- - - - - -	Lb	Ft	Inches	Ft^3		Ft^2	
										WHITEBARK PINE									
192	0	2.5	15	1.5	1.3	0.8	0	0.1587	0.1124	0.0551	0	0	0.18	2.5	1	0.83	1	2	1,500
226	0	4.4	14	4.0	1.6	1.2	0.0066	.2976	.2359	.0529	0	0	.41	4.4	2	3.24	1	[illegible]	3,[illegible]
230	0	3.5	6	2.4	2.1	.5	0	.0816	.0529	.0397	0	0	.17	3.5	1	2.91	1	25	1,567
197	0.2	4.8	26	4.2	1.6	1.3	0	.3241	.2491	.0728	0	0	.70	4.8	2	3.71	1	1	900
195	.4	5.3	25	4.6	1.0	1.0	.0198	.1411	.1235	0	0	0	.42	5.3	2	2.36	1	65	1,597
228	.8	6.5	67	6.1	2.5	1.6	.0463	.6460	.4233	.3064	0	0	1.32	6.5	2	12.36	1	9	4,200
196	1.3	8.0	45	5.5	2.7	1.8	.0529	.9061	.5666	.4850	0	0	2.3	8.0	3	18.03	1	30	6,324
229	1.5	9.8	39	9.0	2.7	2.3	.1411	1.246	.7804	.6680	0	0	3.73	9.8	3	26.71	1	65	2,393
193	1.8	10.0	50	8.2	2.0	2.3	.0088	1.179	.7452	.6195	0	0	5.52	10.0	3	14.00	1	92	1,561
194	2.0	11.3	60	9.7	2.3	2.4	.0220	1.299	.8003	.7253	0	0	6.13	11.3	3	18.80	1	53	3,014
232	3.3	17.9	102	10.5	3.4	3.0	.8466	2.394	1.407	1.477	0	0	20.1	17.9	6	45.83	1	130	5,451
231	3.4	15.0	63	11.1	3.5	4.2	2.668	3.062	1.744	1.975	0	0	13.5	15.0	6	63.33	1	84	1,074
225	4.9	25.1	152	15.8	4.5	4.0	1.543	7.483	3.968	5.247	0	0	65.6	24.6	6	135.3	1	181	3,678
227	5.0	16.9	150	16.1	4.3	6.0	.8973	9.610	4.683	7.359	0	0	28.3	16.1	6	123.9	1	42	3,421
237	6.4	38.4	175	27.4	7.0	5.9	2.156	13.72	6.371	11.17	1.023	0	66.3	27.4	6	587.3	1	81	461
C40	6.7	34.7	200	28.7	7.8	6.5	.7408	--	--	--	--	--	--	--	6	903.9	1	113	2,877
233	7.4	29.7	182	21.2	6.5	6.3	1.795	19.21	8.931	15.92	2.564	--	48.8	19.7	6	538.2	1	99	2,252
C41	9.9	42.2	200	35.4	8.0	9.6	7.421	--	--	--	--	--	--	--	6	1,128	1	110	1,327
C42	10.6	44.0	200	35.5	11.0	10.3	6.815	--	--	--	--	--	--	--	6	1,597	1	92	2,493

Table 15. [illegible]

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Foliage	Live crown weight: Branchwood (inches): 0 to 0.25	0.25 to 1	1 to 3	3 +	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area per acre	Trees per acre
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0119	.1165	0.0860	--	0	0	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0111	.2065	.1218	0.0791	[illegible]	0	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.1477	.1102	0	0	0	[illegible]	[illegible]	1	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.2271	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.1109	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.4012	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.371	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.391	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 13. (con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight: Foliage	Live crown weight: Branchwood (inches) 0 to 0.25	0.25 to 1	1 to 3	3+	Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	Lb					Lb	Ft	Inches	Ft³		Ft²	Number
								STAND III											
825	0	1.3	39	3.4	3.2	0.9	0.0163	0.3333	0.3026	0.1742	0	0	[illegible]	4.3	2	[illegible]	1	[illegible]	[illegible]
827	0	1.3	24	2.4	3.0	.6	.0287	.2271	.1651	0	0	0	.37	4.3	1	[illegible]	1	[illegible]	[illegible]
833	0	3.7	15	2.9	2.8	1.1	.0044	.3880	.2800	0	0	0	[illegible]	3.7	1	[illegible]	[illegible]	[illegible]	[illegible]
834	0	3.7	16	2.7	1.3	.6	.0066	.1808	.1301	0	0	0	.11	3.7	1	[illegible]	[illegible]	[illegible]	[illegible]
841	0	4.0	33	2.6	4.0	.9	.0265	.4453	.2756	.0860	0	0	.41	4.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
832	.3	5.3	28	2.8	4.3	.8	.0066	.2998	.1896	.0529	0	0	.61	7.3	2	[illegible]	1	[illegible]	[illegible]
842	.7	6.4	16	4.8	4.5	1.0	.0265	.4608	.3064	.0507	0	0	[illegible]	6.4	2	32.51	1	[illegible]	[illegible]
838	1.0	9.3	34	9.2	6.0	1.9	.0838	2.191	1.250	.6393	0	0	2.07	9.3	2	[illegible]	1	[illegible]	[illegible]
810	1.3	8.3	45	6.4	4.7	2.2	.1080	2.361	1.389	.6085	0	0	[illegible]	8.3	3	[illegible]	1	91	[illegible]
835	1.5	9.1	48	8.2	5.0	2.6	.0198	4.015	2.130	1.865	0	0	3.34	9.1	3	[illegible]	1	144	[illegible]
807	2.1	12.4	36	9.0	6.8	2.1	.2403	2.710	1.534	.8157	0	0	1.14	12.4	3	[illegible]	1	110	[illegible]
863	2.3	15.9	51	9.6	7.0	2.1	1.290	3.139	1.682	1.426	0	0	8.51	15.9	3	189.1	1	[illegible]	1,171
844	3.0	24.8	80	12.3	5.6	2.5	2.372	4.634	2.438	2.275	0	0	21.0	24.8	4	142.3	1	164	1,524
867	4.1	19.7	48	16.0	10.0	4.2	1.466	12.31	5.842	10.76	0.2976	0	24.1	19.7	6	509.3	1	122	1,718
866	4.3	30.8	37	21.9	7.9	4.1	1.583	10.31	5.168	6.618	0	0	33.3	30.8	6	[illegible]	3	222	[illegible]
870	6.1	31.2	74	23.6	12.0	5.5	4.969	27.53	12.73	26.30	0	0	54.9	26.1	6	932.8	1	[illegible]	[illegible]
882	7.7	54.0	100	39.0	9.8	7.4	19.91	20.72	10.14	15.25	0	0	47.2	28.0	6	3,364	1	[illegible]	[illegible]
872	8.3	43.1	117	30.1	17.0	7.5	5.602	44.08	19.78	53.94	5.807	0	32.7	22.6	6	1,757	1	207	1,136
886	8.4	55.7	98	37.2	10.2	6.9	1.691	28.73	13.47	28.04	11.65	0	55.8	28.3	6	3,098	1	193	[illegible]
885	9.2	59.7	105	52.2	15.1	9.0	13.67	54.00	23.95	75.56	15.16	0	40.1	26.4	6	7,638	1	200	[illegible]
887	10.0	64.8	115	54.6	14.0	9.5	44.21	32.31	14.59	39.77	4.899	0	44.7	21.8	6	[illegible]	1	[illegible]	382
883	11.8	72.4	90	60.4	16.1	10.6	22.84	31.47	13.42	54.15	14.10	0	44.2	23.1	6	7,798	1	[illegible]	858

(con.)

Table 15.--(con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Ht. to crown base	Dead branch weight	Live crown weight: Foliage	Live crown weight: Branchwood	[illegible]	[illegible]	[illegible]	Bole weight	Bole length	[illegible]	Crown volume	[illegible]	[illegible]	Trees per acre
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 13. -(con.)

Tree No.	D.b.h.	Tree height	Age	Live crown length	Crown width	Dia. crown base	Dead branch weight	Live crown weight					Bole tip weight	Bole tip length	Dia. tip base	Crown volume	Site index	Basal area/acre	Trees/acre
								Foliage	Branchwood (inches)										
									0 to 0.25	0.25 to 1	1 to 3	3+							
	Inches	Ft	Yr	Ft	Ft	Inches	Lb	- - - - - -	- - - - - -	Lb	- - - - - -	- - - - - -	Lb	Ft	Inches	Ft^3		Ft^2	
										WESTERN REDCEDAR									
820	0	4.0	26	2.1	2.7	0.7	0.0353	0.2822	0.0794	0.0838	0	0	0.36	4.0	1	6.38	1	70	3,065
831	0	3.7	24	3.0	3.7	.8	.0088	.3086	.0904	.0639	0	0	.21	3.7	1	13.09	1	45	1,898
836	0	4.2	16	3.7	5.4	.8	.0022	.2954	.0860	.0617	0	0	.20	4.2	1	17.63	2	201	1,176
839	0	4.3	24	2.9	6.3	.8	.0309	.3946	.1124	.1124	0	0	.36	4.3	1	27.24	1	124	1,533
809	0.1	5.2	55	3.0	4.8	1.0	.0617	.5467	.1609	.1036	0	0	.78	5.2	2	18.61	1	68	3,110
824	.3	4.7	26	2.5	4.3	.7	.1631	.3461	.1014	.0705	0	0	.56	4.7	2	10.59	1	98	1,723
826	.5	5.8	50	3.3	4.5	.8	.0331	.3329	.0926	.1058	0	0	.57	5.8	2	17.82	1	156	3,611
837	.6	8.0	21	6.1	4.0	1.1	.0419	.6658	.1874	.1984	0	0	.84	8.0	2	21.77	2	140	2,569
818	.7	6.2	37	3.4	4.3	1.0	.0617	.7716	.2183	.2138	0	0	1.09	6.2	2	25.24	1	118	2,187
819	1.3	10.4	40	7.4	5.1	1.8	.0287	2.313	.6327	.8378	0	0	3.00	10.4	3	83.30	1	61	1,962
808	1.4	10.3	43	8.4	5.3	2.0	.2116	2.136	.5776	.8223	0	0	3.02	10.3	3	83.05	1	144	3,516
817	3.5	20.1	64	11.7	8.0	3.0	1.424	5.959	1.552	2.822	0	0	17.3	20.1	6	309.7	1	157	2,418
823	3.7	23.3	70	13.1	11.1	3.0	2.260	6.592	1.676	3.644	0	0	22.3	23.3	6	483.1	1	179	3,526
862	4.0	22.0	57	16.6	13.0	4.0	1.369	11.45	2.961	5.681	0	0	19.1	22.0	6	1,220	1	225	1,569
830	4.8	29.0	58	13.0	5.8	3.3	3.360	11.03	2.703	7.553	1.210	0	44.4	29.0	6	225.7	1	166	2,968
874	6.0	43.7	71	27.2	13.7	5.1	5.827	22.15	5.417	15.43	2.511	0	69.0	38.5	6	2,495	1	335	2,441
859	6.6	43.5	72	20.9	14.5	4.9	9.387	20.71	4.967	16.03	5.465	0	34.9	32.8	6	1,321	2	215	719
864	8.3	55.0	77	24.6	14.7	6.5	20.20	38.83	9.198	32.19	13.15	0	28.8	21.7	6	2,233	1	260	289
880	8.6	51.7	162	27.5	18.3	6.2	5.816	25.75	6.069	22.13	12.91	0	47.0	25.7	6	3,704	1	221	768
875	10.3	51.8	74	37.8	19.8	8.9	9.330	56.50	13.13	53.04	74.62	0	26.9	19.9	6	4,708	1	180	594
879	10.4	52.9	110	41.5	12.3	8.4	9.456	27.26	6.444	22.93	13.53	0	49.8	22.0	6	5,958	1	300	169
865	10.6	64.3	70	39.9	22.4	8.2	17.82	61.29	14.28	55.69	36.07	0	28.8	22.7	6	7,764	2	240	332

Table 11. [illegible]

D.B.H. (inches)	[illegible]	L	S	[illegible]	[illegible]	[illegible]	PP	[illegible]	[illegible]
[illegible]-5.9	1	[illegible]	[illegible]	[illegible]	1	1	1	1	1
6- 9.9	1	1	[illegible]	[illegible]	[illegible]	[illegible]	1	3	1
10-13.9		6	2	[illegible]	1	[illegible]			5
14-17.9	5	11	[illegible]	4	11	[illegible]	[illegible]	11	1
18-21.9	6	11	[illegible]		5	1	[illegible]	[illegible]	[illegible]
22-25.9	3	[illegible]	6		1		1		[illegible]
26-29.9		1	2						
30-33.9						1			
34-37.9	1	2				[illegible]			
38-43.9	1								
Total	15	36	[illegible]	41	[illegible]	17	[illegible]	[illegible]	[illegible]

APPENDIX III

Foliage and Branchwood Proportions

Table 15.--*Foliage and branchwood proportions for crowns of trees 1 inch and less in d.b.h.*

Crown	Species	Foliage	Branchwood 0 to 0.25	Branchwood 0.25 to 1
Live Dominants	S, AF, C, GF, WH	0.62	0.26	0.12
	DF, WP, LP, WBP	.52	.27	.21
	PP	.57	.14	.29
	L	.40	.42	.18
Live Intermediates	DF, GF	.55	.39	.06
	PP, C	.63	.20	.17
Dead Intermediates	DF, GF, PP, C		.94	.06

able 16. [illegible]

pe ass	Function	r	Conditions
	P1 = [illegible]	.91	[illegible]
	P2 = [illegible] 1.150 [illegible]	[illegible]	
	P3 = [illegible]	.9[illegible]	[illegible]
	P1 = [illegible]	[illegible]	
	P2 = 0.745 EXP(-0.0362d)	.95	
	P3 = [illegible]	[illegible]	[illegible]
	P4 = [illegible]	[illegible]	[illegible]
S	P1 = [illegible]	[illegible]	[illegible]
	P2 = [illegible]	.9[illegible]	
	P3 = [illegible]	[illegible]	[illegible]
A	P1 = 0.597 EXP(-0.0425d)	.74	
	P2 = 0.864 EXP(-0.0375d)	.72	
	P3 = [illegible]	[illegible]	[illegible]
L	P1 = [illegible]	[illegible]	
	P2 = [illegible]	[illegible]	
	P3 = [illegible]	[illegible]	[illegible]
W	P1 = [illegible]	.95	
	P2 = 0.914 - 0.0978√d	.91	
	P3 = [illegible]	[illegible]	[illegible]
WP	P1 = [illegible]	[illegible]	[illegible]
	P2 = 0.864 EXP(-0.0585d)	.75	
	P3 = [illegible]	[illegible]	[illegible]
C	P1 = [illegible]	[illegible]	
	P2 = 0.756 EXP(-0.0241d)	.98	
	P3 = [illegible]	[illegible]	[illegible]
T	P1 = [illegible]	[illegible]	[illegible]
	P2 = 0.625 EXP(-0.0511d)	.89	
	P3 = [illegible]	[illegible]	[illegible]
	P4 = [illegible]	[illegible]	[illegible]
H	P1 = [illegible]	.95	[illegible]
	P2 = 0.729 EXP(-0.0233d)	.95	
	P3 = [illegible]	[illegible]	[illegible]
	P4 = [illegible]	[illegible]	[illegible]
H	P1 = [illegible]	[illegible]	[illegible]
	P2 = 0.835 EXP(-0.0380d)	.97	
	P3 = [illegible]	[illegible]	[illegible]

Table 17.--*Accumulative proportions of foliage and branchwood by size classes for live crowns of intermediates greater than 1 inch d.b.h.*

Species	Function	R^2	Conditions
C	P1 = 0.667 EXP(-0.0608d)	0.93	
	P2 = 0.857 EXP(-0.0653d)	.94	
	P3 = 1.031 EXP(-0.0270d)	.73	If d $\leq$1.0, P3 = 1.0
GF	P1 = 0.571 EXP(-0.0544d)	.93	
	P2 = 0.929 EXP(-0.0678d)	.93	
	P3 = 1.016 EXP(-0.0098d)	.59	If d $\leq$1.0, P3 = 1.0
DF	P1 = 0.514 EXP(-0.0552d)	.74	
	P2 = 0.886 EXP(-0.0610d)	.75	
	P3 = 1.0067 EXP(-0.0131d)	.38	If d $\leq$1.0, P3 = 1.0
PP	P1 = 0.650 EXP(-0.154d)	.79	
	P2 = 0.844 EXP(-0.166d)	.80	
	P3 = 1.086 EXP(-0.0833d)	.75	If d $\leq$1.0, P3 = 1.0

Table 18. [illegible]

Species		Function	[illegible]	Condition
		[illegible]		
GF	P1	[illegible]	[illegible]	[illegible]
	P2	1.26[illegible] EXP([illegible])	.1[illegible]	[illegible]
				[illegible]
DF	P1	0.083[illegible] + (1.5[illegible]d)	.8[illegible]	[illegible]
	P2	1.567 EXP(-0.0525d)	.5[illegible]	[illegible]
[illegible]	P1	1.460d^(-2.[illegible])	[illegible]	[illegible]
	P2	1/(0.84[illegible] + 0.01[illegible]	[illegible]	[illegible]
M	P1	1.210d^([illegible])	[illegible]	[illegible]
LP	P1	1.5[illegible]	.95	[illegible]
	P2	2.798 EXP(-0.126d)	.7[illegible]	[illegible]
				[illegible]
				If d <1.5 in, P1 = 1.0
WF	P1	1.0077d^([illegible])	.49	
	P2	1.02[illegible] - 0.00490d	.12	If d <7.0 in, P2 = 1.0
C	P1	-0.0158 + (1.4674d)	.87	If d <1.5 in, P1 = 1.0
	P2	1.15[illegible] EXP(-0.[illegible]d)	[illegible]	[illegible]
PP	P1	1.4117d - 0.0451	[illegible]	[illegible]
	P2	1.06[illegible] - 0.0754d	.69	If d >30.0 in, P2 = 0.06
WH	P1	1.961 EXP(-0.206d)	.7[illegible]	[illegible]
	P2	1.0/(0.27[illegible] + 0.0614d)	[illegible]	[illegible]
				If d <12.0 in, P2 = 1.0
		INTERMEDIATE		
C	P1	0.361d^([illegible])	.60	
GF	P1	1.549d^(-[illegible].08[illegible])	.81	[illegible]
				[illegible]
DF	P1	0.0790 + 1.2[illegible]d	.46	[illegible]
				If d <1.4, P2 = 1.0
PP	P1	0.513d^(-1.[illegible])	.4[illegible]	[illegible]
	P2	1/0.379 + 0.180d	[illegible]	If d <5.4, P3 = 1.0

Table 19.--*Accumulative proportions of foliage and branchwood by size class for entire trees less than 15 feet in height*[1]

Species[2]	Height (feet)	No. sample trees	Foliage	Branchwood (inches) 0 to 0.25	0.25 to 1	1 to 3	3+
DOMINANTS							
C, GF, S, AF	0- 4.9	17	0.51	0.72	0.95	1.00	
	5- 9.9	26	.40	.56	.73	.99	1.00
	10-14.9	11	.33	.45	.63	.92	1.00
WP	0- 4.9	4	.48	.69	.99	1.00	
	5- 9.9	8	.31	.47	.65	1.00	
	10-14.9	5	.25	.37	.52	.89	1.00
DF, PP, LP, H	0- 4.9	16	.38	.56	.94	1.00	
	5- 9.9	23	.31	.45	.68	1.00	
	10-14.9	14	.27	.38	.57	.87	1.00
L, WBP	0- 4.9	9	.26	.49	.87	1.00	
	5- 9.9	7	.21	.40	.66	1.00	
	10-14.9	8	.15	.29	.45	.89	1.00
INTERMEDIATES							
C, GF	0- 4.9	10	.38	.56	.96	1.00	
	5- 9.9	9	.32	.47	.76	1.00	
	10-14.9	3	.41	.55	.71	1.00	
DF	0- 4.9	4	.34	.59	1.00		
	5- 9.9	4	.23	.40	.67	1.00	
	10-14.9	1	.25	.42	.58	1.00	
PP	0- 4.9	4	.24	.32	.91	1.00	
	5- 9.9	5	.18	.23	.51	1.00	
	10-14.9	2	.16	.19	.43	.99	1.00

[1] Coefficients of variation averaged over the foliage and branchwood categories of all species groups were 16, 17, and 25 percent for the 0- to 4.9-foot, 5- to 9.9-foot, and 10- to 14.9-foot height classes, respectively.

[2] Fractions for individual species are within 20 percent of the group average.

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[illegible]

crown bulk density.

[illegible]

crown bulk density.

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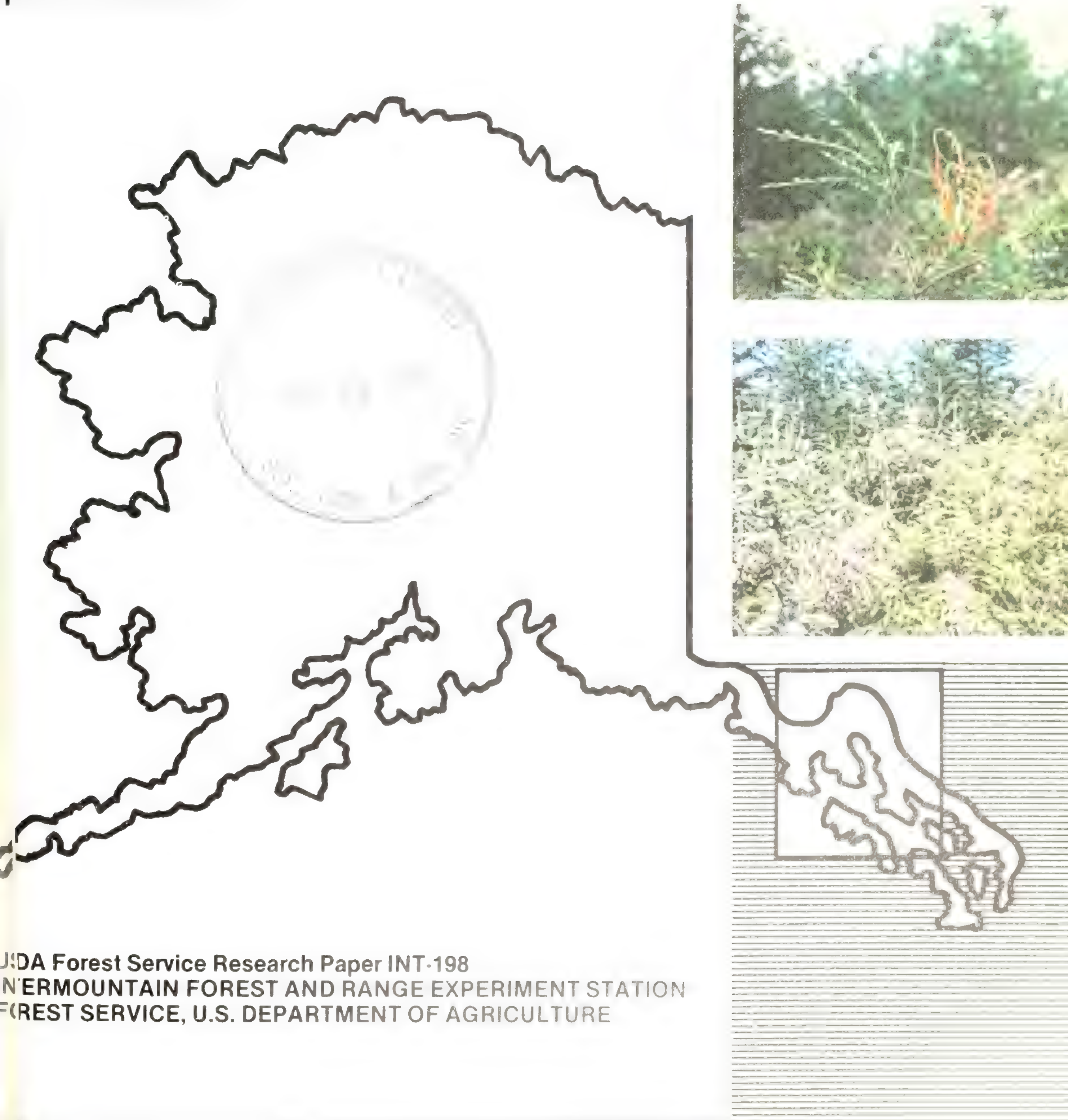
SIROCOCCUS SHOOT BLIGHT DAMAGE TO WESTERN HEMLOCK REGENERATION AT THOMAS BAY, ALASKA

Ed F. Wicker
Thomas H. Laurent
Spencer Israelson



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SIROCOCCUS SHOOT BLIGHT DAMAGE TO WESTERN HEMLOCK REGENERATION AT THOMAS BAY, ALASKA

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RESEARCH SUMMARY

Clearcut areas regenerated to western hemlock and Sitka spruce in southeast Alaska were surveyed for damage by Sirococcus shoot blight. A disease index was calculated for potential crop trees. All Western hemlock regeneration was infected. Disease severity was greater in suppressed and intermediate than in dominant and codominant crown classes. Mortality and severe top-killing were restricted to suppressed and intermediate crown classes. Disease severity was greater in lower than in the upper crown of potential crop trees. Terminal leader kill in potential crop trees was common. Direct measures of disease control are not recommended.

INTRODUCTION

Shoot blight of western hemlock [*Tsuga heterophylla* (Rafn.) Sarg.] regeneration n southeast Alaska (fig. 1) was observed first in 1967 on the mainland, 12 mi NNE of Ptersburg at Thomas Bay (Baker and Laurent 1974). Funk (1972) identified the causal gent as *Sirococcus strobilinus* Preuss. He demonstrated its pathogenicity by inoculatig young trees and reisolation from diseased tissues. Since its discovery, the disease hs been closely monitored by Insect and Disease Control and Timber Management personnel of the Alaska Region (Baker and Curtis 1973; Baker and Laurent 1974; Baker and others 175; Crosby and Curtis 1968, 1970; Curtis and Swanson 1972; Hostetler and others 1976). Te disease is spreading. It is now known to occur at several locations in southeast Aaska as far north as Juneau. A high intensity of infection continues to exist at Tomas Bay. In 1972, Sitka spruce [*Picea sitchensis* (Bong.) Carr.] regeneration also ws observed to be affected by the disease (Baker and Curtis 1973).

Sirococcus shoot blight of conifer seedlings and saplings is known to occur in mny areas of the world. Little information is available concerning its potential to dmage natural regeneration (Graves 1914; Kujala 1950; Lagerberg 1933; O'Brien 1973; Rbak 1956). This report presents quantitative data of damage caused by *S. strobilinus* t western hemlock regeneration at Thomas Bay, Alaska. Significance of this damage to fture management of these young stands is discussed.

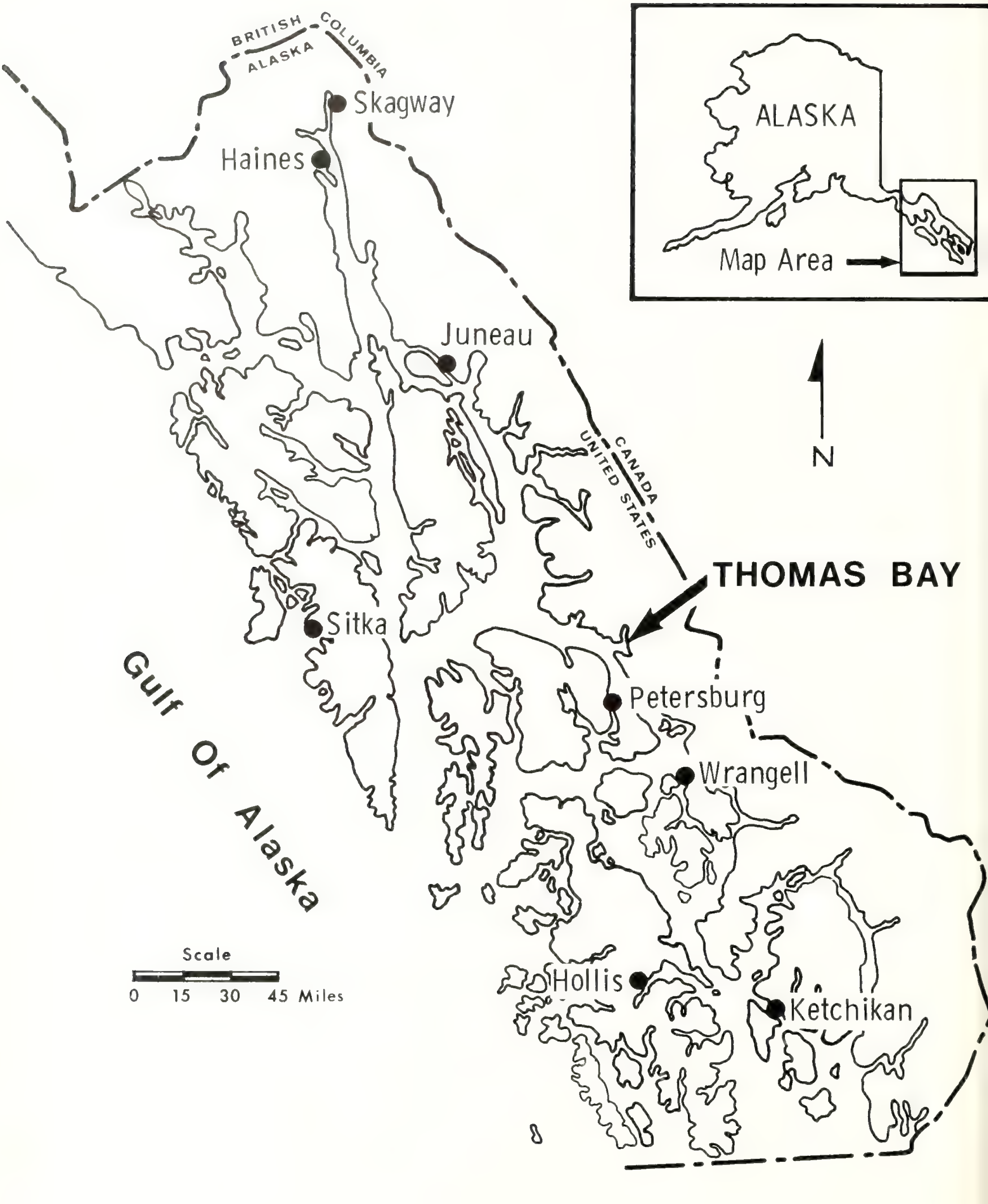


Figure 1.--Map of southeastern Alaska. Sirococcus *shoot blight was discovered at Thomas Bay in 1967, has now spread north to Juneau.*

MATERIALS AND METHODS

Four clearcut areas, supporting natural regeneration of western hemlock and Sitka spruce less than 20 years old, were sampled. Areas were selected on the basis of comparable age, stand origin, macroclimate, and documented occurrence of *S. strobilinus*. Clearcuts were from 0.2 to 0.5 mi apart and all on recent glacial outwash. One of the four areas had been thinned; the other three were unthinned.

The three unthinned areas had been clearcut in 1959-1962, so the oldest regeneration was 16 years. One of these areas had received 464 kg Agricultural Grade urea/hectare in May 1969; the two remaining areas were untreated. A line of 4 plots, 100 m apart and 4 m^2 area, was established in each of the three areas. Total number of (1) trees, (2) infected trees, (3) dead trees, and (4) potential crop trees (dominants or codominants) were recorded for each plot.

Five potential crop trees were selected from each plot for second-order sampling. These trees were cut at ground line and removed from the plot. Total height, total number of branches, and year of dead terminal leader (6 years accumulation) were recorded for each tree. Six primary branches (two lower, two middle, and two upper crown) were removed from each tree and used for third-order sampling. Total length of rimary, secondary, tertiary, etc., branching and total length of branching with ymptoms of *Sirococcus* infection were recorded for each primary branch sampled. The atio of infected branch length:total branch length for the tree was calculated and sed as a disease index. An analysis of variance was conducted for the disease index ata from the three unthinned areas, using the following model for an unbalanced design (Snedecor 1959):

$$Y = \mu + \gamma_{i} + \alpha_{j(i)} + \Sigma_{ijk}$$

here

Y = dependent variable

μ = mean

γ_{i} = treatment

$\alpha_{j(i)}$ = plot nested in treatment

Σ_{ijk} = error

The fourth area sampled was a 0.4 ha plot that was mechanically thinned in 1975 to a 2.4 × 2.4 m spacing. Maximum age of the regeneration was 20 years. Twelve western hmlock trees, comparable in size, were selected from the plot and sampled in the same mnner as those from the previous three areas. The disease index data were not included i the analysis of variance because the severely infected western hemlock was removed dring the recent thinning and Sitka spruce was favored in selection of crop trees.

RESULTS

Unthinned areas.--The three areas examined were overstocked (table 1). More tha 90 percent of the conifer regeneration was western hemlock. The remaining conifer regeneration was Sitka spruce. Considerable amounts of broad-leaf shrubs also occupi the sites.

All the western hemlock regeneration was infected by *S. strobilinus* (fig. 2). Infection was most severe on regeneration in the suppressed and intermediate crown classes. Some of this regeneration showed severe top-killing (table 1) and a bushy, broomlike growth form with no definitive terminal leader (fig. 3). It is likely that earlier in the life of the stand, many of these individuals were dominants and codominants; the disease cost them their dominant position. All mortality attributed to th disease (table 1) was in the suppressed and intermediate crown classes.

Recent (1975 and 1976) leader kill in potential crop trees (fig. 4) was common. The accumulative leader kill over a 6-year period was high (table 2). No mortality or severe top-kill (fig. 3) was recorded for potential crop trees. Disease was more severe in the lower crowns and least in the upper crowns in all trees examined.

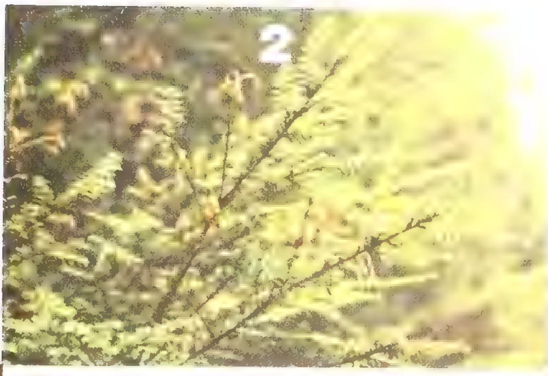
Analysis of variance showed a significant difference (P=0.05) in disease index between areas and plots. We believe these differences are related to local environmental factors not measured during the study (Wall and Magasi 1976).

No infection of Sitka spruce was recorded on the plots examined. However, while moving from plot to plot, an occasional infected Sitka spruce (fig. 5) was observed.

Table 1.--*Stocking, infection, and mortality data/hectare for western hemlock and Sitka spruce regeneration, Thomas Bay, Alaska*

Area	Total trees[1]	Crop trees[1]	Infected trees[2]	Dead trees[3]	Top-kill trees
	No.	- - - - - -	- - - - *Percent*	- - - - - -	- - - - - -
1	59,500	23.1	93.7	10.5	13.4
2	86,250	18.8	91.9	12.2	34.8
3[4]	55,000	32.7	90.9	21.4	20.5
4[5]	1,663	100.0	100.0		

[1] Includes Sitka spruce.
[2] Represents 100 percent of western hemlock.
[3] All were in the intermediate and suppressed crown classes.
[4] Fertilized May 1969; 464 kg Agricultural Grade urea/hectare.
[5] Area thinned in 1975 to 2.4 × 2.4 m spacing.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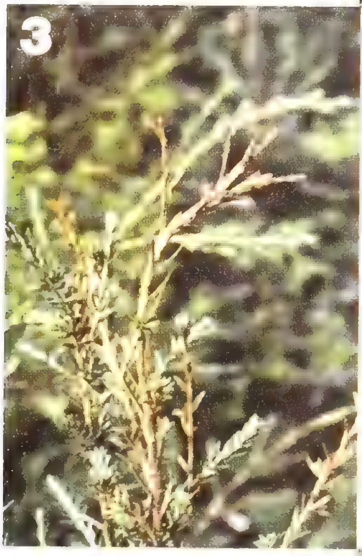
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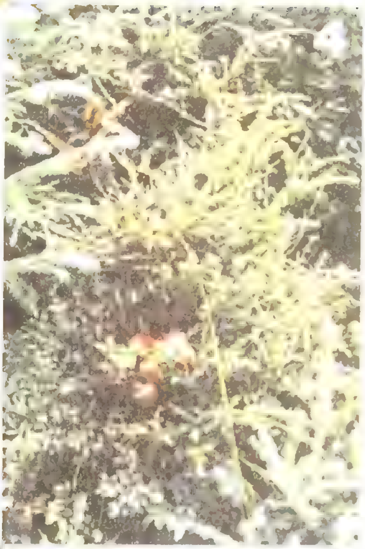
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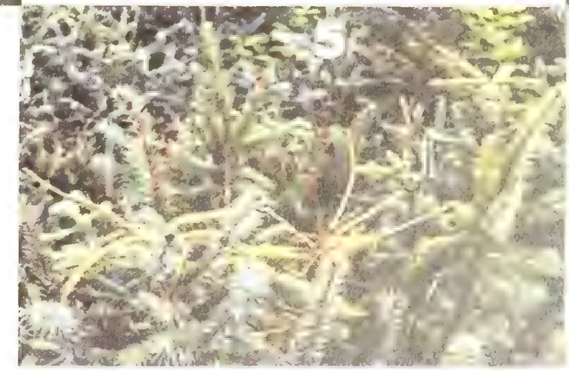
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[illegible]
[illegible]
[illegible] Sirococcus strobilinus. [illegible]

Table 2.--[illegible]

Area	Height	Total branching	Dead branching	Disease index[1]	[illegible]
	- - - - - - - - -	*Meters* - - - - - - - - -			[illegible]
1	2.96	398.1	36.2	0.091 a	63.2
2	2.64	224.6	51.7	.141 b	80.0
3[3]	2.81	326.0	61.0	.187 c	75.0
4[4]	4.16	680.0	54.9	.081	42.0

[1] Means followed by a different letter are significantly different (p=0.05; Duncan Multiple Range Test). Area No. 4 not included in analyses.

[2] Accumulative for 1971-1976.

[3] Fertilized May 1969; 464 kg Agricultural Grade urea/hectare.

[4] Thinned in 1975 to 2.4 × 2.4 m spacing.

Thinned area.--Thinning was accomplished only 15 months prior to the disease survey. Therefore, comparisons between the thinned and unthinned areas must be conditioned. The average potential crop tree was larger on the thinned area than on the unthinned areas (table 2) because it was 4 years older and largest trees were selected as crop trees. Disease index and percentage terminal kill were lower than on the unthinned areas (table 2) because severely infected trees were removed during the thinning. These data indicate good quality control in the selection of crop trees during the thinning operation. The ratio of Sitka spruce to western hemlock is higher in the thinned than in the unthinned areas. This was intended since Sitka spruce was favored i leave tree selection.

Fertilized vs. nonfertilized areas.--The fertilized area had the lowest overall socking of the unthinned areas (table 1). However, the number of potential crop trees ws much higher than on the nonfertilized areas. Percentage dead trees in the suppessed and intermediate crown classes was twice that of the nonfertilized areas. Prcentage top-kill trees in these crown classes was intermediate between the two nonfrtilized areas. Disease index for potential crop trees on the fertilized area was te highest of all areas examined (table 2).

DISCUSSION

Western hemlock is a climax species. It is very tolerant of shade and well ad to growth as a crowded, suppressed understory in areas of high precipitation. Deve ment of *Sirococcus* shoot blight is favored by conditions of high atmospheric moistu mild temperatures, and low light intensities (Funk 1972; Peterson and Smith 1975; S 1973). Spores of the causal fungus are disseminated by splashing of water drops (Peterson and Smith 1975). The spores infect only juvenile needles and the disease kills new shoots (Peterson and Smith 1975). Such environmental requirements expla why disease severity is greater in regeneration of suppressed and intermediate crow classes than in potential crop trees. Environments of overstocked western hemlock forest ecosystems in southeast Alaska are ideal for optimum development of the susc and the disease.

The highest disease index was 0.187 for the fertilized area. This means that 18.7 percent of the branching has been killed by the disease. Unfortunately, there no opportunity during this investigation to sample a comparable area of western hem regeneration that was disease-free. Neither can we find published data adequate fo quantitative comparisons. Therefore, we cannot express the disease index in quanti tive terms of growth reduction.

Sirococcus shoot blight reduces tree growth because it reduces photosynthetic sue and causes a net loss in carbohydrates. Food for tree growth is produced by ac photosynthesis or may come from stored reserves. Young conifer needles are more ef cient in photosynthesis than are older ones. Likewise, branches in the upper crown exposed to full sunlight are more efficient than those in the lower crown. Branche in the partially shaded lower crown may not produce enough food to maintain their growth. In some conifers, little or no additional food is translocated to these branches and they die. This process, called natural pruning, is very common in sha intolerant species. In other conifers, food manufactured in other parts of the cro is translocated to branches inefficient in photosynthesis, and they remain alive. branches are parasitic on the tree and natural pruning is minimal. Therefore, compa sons of the effects of foliage removal by artificial or natural pruning from below equal amounts of defoliation by a foliage disease are not valid. *Sirococcus* shoot blight is selective. It kills those tissues most efficient in photosynthesis; youn needles.

When photosynthetic tissue and carbohydrate losses are so great that active pho synthesis cannot supply the food necessary for growth, then it must come from store reserves. When this condition persists for a time sufficient to deplete these rese tree death is eminent. Levels of mortality and severe top-killing (table 1) of rege eration in suppressed and intermediate crown classes signify that the above conditi prevails in these crown classes.

In view of current stocking levels, we consider the above condition as beneficial to management of the areas for timber production. Trees in suppressed and intermediate crown classes represent surplus stocking (table 1). Their presence provides undesirable competition for potential crop trees. The disease is effecting a natural thinning in these crown classes. This will reduce competition and enhance growth and dominance of potential crop trees. Unfortunately, the rate of natural thinning is inadequate for optimal growth release.

The disease situation in potential crop trees is very different from that recorded for suppressed and intermediate crown classes. No mortality or severe top-killing was recorded. Disease damage was much greater in shaded, lower portions of crowns than in upper crowns. Although periodic terminal leader kill has reduced total height, it has not caused any major stem deformity. Such damage can be detected only by closeup, detailed examination of upper stems. Leader kill occurring more than 6 years ago is no longer discernible. Normal growth form has not been altered.

The greatest differences between the fertilized and nonfertilized areas were in mortality and percentage of potential crop trees. The slight reduction in stocking level of the fertilized area can be explained by a higher mortality level (table 1). Our sampling was not adequate to estimate the total variation in disease severity within and between the unthinned areas. We believe the higher percentage of potential crop trees in the fertilized area is a direct result of the fertilizer treatment. The addiional nutrients enhanced growth of the seedlings and permitted a greater number to express dominance earlier. The high density of dominants and codominants created environmental conditions, within these crown classes, more favorable for infection and isease development. The result was a higher disease index for potential crop trees n the fertilized area.

CONCLUSIONS AND RECOMMENDATIONS

We conclude that the current level of *Sirococcus* blight in potential crop trees in outheast Alaska is no cause for alarm. This conclusion is based on our data and knowedge of the suscept and the disease. We believe the disease to be native to the area. nfections were found in western hemlock more than 300 years old. The disease is not estricted to young regeneration, but it is more noticeable in this material. No irect disease control measures are recommended at this time (Smith and others 1972). onitoring of the disease in southeast Alaska should continue.

Sirococcus strobilinus is reducing height growth of western hemlock by killing the erminal leaders. However, competition is the major cause of growth reduction in areas urveyed at Thomas Bay. The regeneration is over 15 years old and dominance has been xpressed. We recommend that Timber Management personnel thin these stands to stocking evels established for the Alaska Region. This will not only enhance growth of selected rop trees, but will create environments less favorable for development of *Sirococcus* hoot blight. The mixture of western hemlock and Sitka spruce should be maintained in reasonable facsimile of their natural ratio.

The unthinned areas illustrate some adverse effects of overstocking. We concl that the fertilizer treatment prior to thinning has compounded these adverse effect We recommend that future applications of fertilizer be made after, not prior to, th ning. This will ensure that increased growth will be concentrated on those stems selected for future crop trees.

Establishment of nurseries in southeast Alaska for production of western hemlo planting stock would be a high risk adventure. *Sirococcus strobilinus* is capable o causing severe losses in nurseries because the environment usually favors developme of disease. If western hemlock planting stock is needed, we would recommend produc by containerized methods in greenhouses. A subirrigating system, a forced-air vent tion system, and a supplemental lighting system would be required to maintain a relatively blight-free environment.

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Clearcut areas regenerated to western hemlock at Thomas Bay in southeast Alaska were surveyed for damage by *Sirococcus* shoot blight. A disease index was calculated for potential damage. [illegible] of western hemlock regeneration was infected.

KEYWORDS: *Sirococcus strobilinus*, [illegible]

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GROWTH AND NUTRITIONAL VALUE TO CATTLE OF GRASSES ON CHEATGRASS RANGE IN SOUTHERN IDAHO

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RESEARCH SUMMARY

Seven grass species--desert wheatgrass (*Agropyron desertorum*), streambank wheatgrass (*Agropyron riparium*), cheatgrass (*Bromus tectorum*), basin wildrye (*Elymus cinereus*), Sandberg's bluegrass (*Poa sandbergii*), bottlebrush squirreltail (*Sitanion hystrix*), and needle-and-thread grass (*Stipa comata*)--were harvested to a 1/2-inch (1.2-cm) stubble height periodically between mid-March and December in most years from 1962 through 1968 at the Saylor Creek Experimental Range in southern Idaho. These samples were analyzed for N, P, S, Ca, Mg, K, Na, Zn, Mn, Cu, and Fe. Certain digestibility fractions (NDF, NDF-ash, DCW, DCW-ash free, and TDDM) were also determined on these samples. In addition, estimates of the soil chemical status, soil moisture contents over depth and time, forage yields, and moisture contents over time, effects of ammonium nitrate fertilization on forage yields and mineral composition, and animal grazing responses to cheatgrass range are included.

Trends in mineral concentration; mineral ratios Ca:P, K:(Ca + Mg), N:S, Zn:Ca, and Zn:Cu; and digestibility fractions were plotted over time in a series of graphs. When a significant r^2 value was determined for a given parameter and plant species through regression analysis, the equation and line describing the trend are given.

There was a distinct exponential decrease in plant tissue mineral concentration for each nutrient studied, except for Na, Mn, and Fe, which did not exhibit any trends in any species. In cheatgrass, Ca and Mg declined with plant maturity, but in the other species no trends could be detected. The Ca:P ratio increased exponentially, while the equivalents of K:(Ca + Mg) and N:S ratios decreased as plants matured. Ratios of Zn:Ca and Zn:Cu were unrelated to plant maturity. Total fiber (NDF) increased and tended to level as the forage matured. Digestibility, including cell wall digestibility (DCW), organic cell wall digestibility (DCW-ash free), and total dry matter digestibility (TDDM) decreased as plants matured. There were differences in the levels of these components between species, but the trends were as expected.

Organic N, K, Mn, and Fe concentrations were greater near the soil surface and decreased with depth in the soil. Although the organic N levels appeared adequate for these soils, results from a fertilization trial with N indicated that available N was limiting plant growth at least for the soil moisture conditions during the study period. Nitrogen levels in the seven species were inadequate after late June, and consideration should be given to crude protein supplementation of grazing animals.

Fertilization was shown to increase forage yields and N levels, but costs of fertilizing to increase crude protein concentration may be prohibitive compared to direct animal supplementation.

In spite of apparently adequate levels of K in the soil, plant K decreased rapidly with time and soon reached levels below those considered necessary for good nutrition in cattle. Manganese levels were adequate for animal nutrition through the season and showed no relationship to plant maturity. Iron levels were generally much higher than normally found in plant tissue. Measured Fe levels varied widely, probably because of soil contamination.

By the end of June, the level of plant P was below recommended allowances for cattle. Plant Zn levels were adequate for a brief period in the spring, and then declined to a level where supplementation has been shown to be beneficial for weight gains. Copper showed declining trends in five of seven plant species, but never declined below levels considered adequate.

Sulfur, as the sulfate ion, is readily leached in soils. We found that S was accumulating deep in the soil profile below the normal depth of plant roots. Levels of S in the plants declined rapidly between April and June. The N:S ratio also declined as plants matured and could reduce the protein conversion efficiency. However, cheatgrass, which comprises the bulk of the forage, maintained an N:S ratio considered adequate, but the low forage S in itself could be a problem.

Calcium and Mg are very abundant in Saylor Creek soils, and the levels found in plant tissues were considered adequate for cattle. Other factors, not considered here, may reduce Mg availability to ruminants particularly in the early spring, causing Mg deficiency. The amount of K in relation to Ca and Mg has been implicated in grass tetany problems. Basin wildrye and desert wheatgrass had equivalents of K:(Ca + Mg) ratios above 2.2 for portions of the spring period. On cheatgrass range, grass tetany is not likely to be a problem except where desert wheatgrass seedings are used in a management program. The Ca:P ratio increased as plants matured, and all species except desert wheatgrass and cheatgrass exceeded the recommended 7:1 level by late October.

Sodium was found in relatively large amounts in the soil below the normal rooting depth of our species. Plant tissue Na concentrations were variable with time, but were less than those considered adequate for cattle; however, normal management includes the provision of NaCl salt blocks.

No trends were found for the Zn:Ca and Zn:Cu ratios with plant maturity.

As indicated by TDDM measurements, most species were less than 60 percent digestible by September. Apparent dry matter digestibility or TDN was about 13 units lower. Comparative work with esophageal fistulated yearling cattle and lignin and chromic oxide techniques gave dry matter digestibilities of 65 percent in early September. These differences may reflect selective feeding on the part of the animals.

On cheatgrass range, fertilization with N increased yields and N contents, but had little effect on plant uptake of other minerals. Similar results were found on fertilized needle-and-thread grass range, but the increased yields were not economical. These results imply that fertilization on these two range types, under semiarid conditions, is not practical and that direct animal supplementation of needed nutrients could be practiced instead.

Cheatgrass range provided considerable forage that is nutritious in spring and early summer. Yearling cattle response to cheatgrass range under a variety of treatments has shown that this class of animals can make satisfactory weight gains without supplementation. However, it has been shown that these animals will perform somewhat better when protein and energy are added to their diets. Calves, in particular, are likely to benefit from Zn supplements, especially late in the season.

INTRODUCTION

Cheatgrass (*Bromus tectorum*)[1] range occurs widely in the Intermountain and Colum- ia basins and supports large numbers of livestock. This fall-germinating annual was ntroduced into North America from Europe about 1850 and spread rapidly across western angelands until today it covers an estimated 60 million acres in the 11 western States Hull 1965). In southern Idaho, cheatgrass is dominate on an estimated 6 to 7 million cres and is an important species on another 20 million acres.

Hull and Pechanec (1947) considered cheatgrass the most important forage plant in outhern Idaho, and the associated species seasonally or periodically important. Gras- es on these semiarid ranges are nutritious in the spring but mature rapidly, resulting n a forage quality decline. Murray and Klemmedson (1968) found that yearling cattle ains were greatest in the late spring when nutrient levels were still adequate and orage was abundant. Gains declined throughout the summer and fall as the forage cured nd deteriorated.

Livestock performance is partially dependent upon adequate levels and favorable alances of nutrients in the forage consumed. Forage should contain at least the inimum balanced nutritional levels for maintenance and greater amounts for growth and ain. Since grass nutrient levels vary from one stage of development to another (Cramp- on and Jackson 1944; Cook and Harris 1950; Phillips and others 1954), the nutrient ntake may be inadequate during part of the grazing season. An understanding of nutri- nt changes in range plants throughout the grazing season will give stockmen and man- gers information needed to develop supplementation programs, or to change management stems to enhance livestock performance.

The need to improve livestock performance on cheatgrass ranges prompted the esearch reported here. Our objectives were: (1) to determine the trends (over the pril to November grazing season), and some of the causes of these trends in nutrient ontents and digestibility fractions for seven grass species: desert wheatgrass *gropyron desertorum*), streambank wheatgrass (*Agropyron riparium*), cheatgrass (*Bromus ectorum*), basin wildrye (*Elymus cinereus*), Sandberg's bluegrass (*Poa sandbergii*), ottlebrush squirreltail (*Sitanion hystrix*), and needle-and-thread grass (*Stipa comata*); nd (2) to develop equations which describe these trends and make it possible to pre- ct dates of probable mineral deficiencies.

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[1] A list of species with complete scientific and common names is given in appendix I. omenclature follows Hitchcock and Cronquist (1973).

EXPERIMENTAL AREA

The Saylor Creek Experimental Range was formerly a joint facility of the Bureau Land Management, U.S. Department of Interior, and the Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. All plant, soil, and animal weight gain data were collected at the Saylor Creek Experimental Range 9 miles (15 km) southwest of Glenns Ferry, Idaho. The experimental area occupies appro imately 4,400 acres (1,780 ha) of rangeland at an elevation of 3,140 feet (957 m). Air temperature and precipitation data were obtained from the climatological station at Glenns Ferry at 2,600 feet (800 m) elevation.

The climate at the Saylor Creek Experimental Range is semiarid. Annual precipitation varies from about 5 inches (125 mm) to slightly under 19 inches (480 mm), base on long-term records from Glenns Ferry. Average monthly precipitation for 1961 throu 1974 is shown in figure 1. Precipitation in 6 of these 14 years exceeded the 40-year long-term average of 9.6 inches (240 mm).

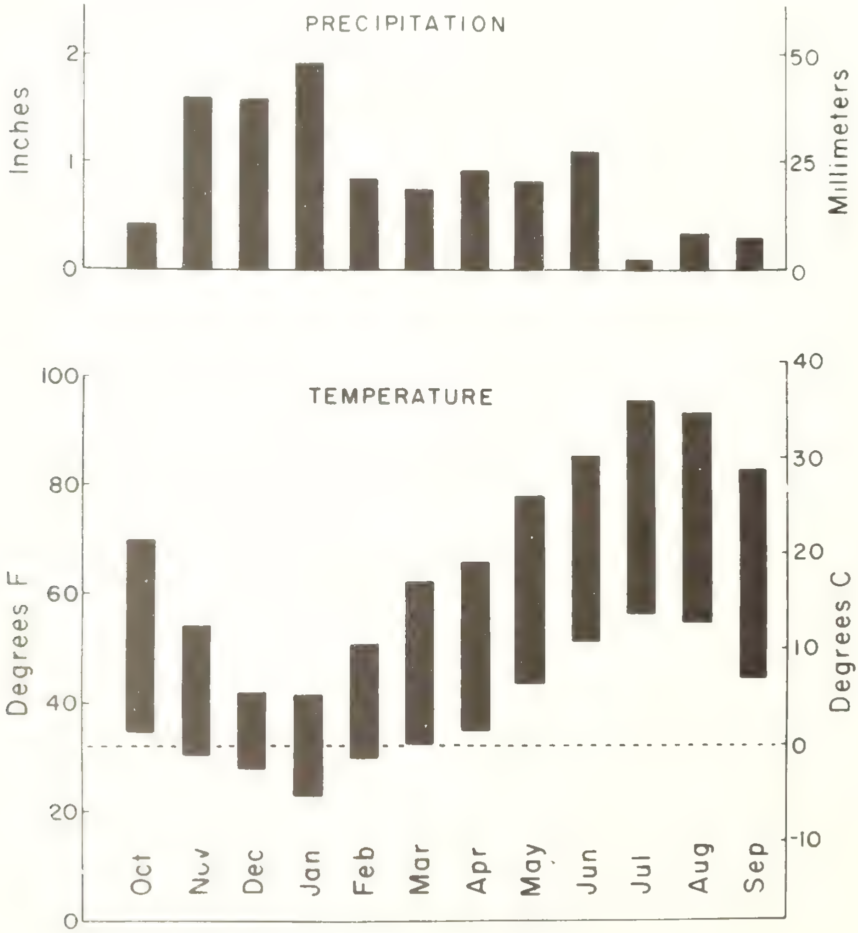

Figure 1.--Avera
monthly precip
tion and the r
between averag
maximum-minimu
temperatures f
Glenns Ferry,
(1961 through

Low winter temperatures may reach -25° F (-32° C) and high summer temperatures frequently exceed 100° F (38° C). Average monthly maximum-minimum temperatures for 1961 through 1974 are depicted in figure 1.

Remnants of the original vegetation still present on some of the Saylor Creek Experimental Range indicate that the former vegetation for the area was a basin big sagebrush-needlegrass (*Artemisia tridentata* ssp. *tridentata-Stipa thurberiana*) type. Natural invasion of cheatgrass, fire, and subsequent heavy grazing of native species by cattle (primarily) and sheep have each played a role in altering this type drastically, leaving a range dominated by cheatgrass-bluegrass with varying amounts (depending upon locality) of bottlebrush squirreltail, streambank wheatgrass, basin wildrye, needle-and-thread grass, Russian thistle, tansy mustard, and other annual and perennial grasses and forbs. Fire has had a major impact on the vegetational succession observed on these ranges.

The experimental range has several acres of remnant sagebrush-grass range, which is in fair condition. Approximately 100 acres (40 ha) have burned and are now dominated by needle-and-thread grass. Interspersed in the cheatgrass and needle-and-thread grass range are clones of other species, including patches of streambank wheatgrass in the shallow swales, varying in size from a few plants to 0.05 acre (0.02 ha).

Percent composition of annual species vegetation at Saylor Creek varies considerably from year to year, and within years, depending on season, grazing intensity, and timing and amount of precipitation. Percent frequency was used to measure the change in species in two nongrazed cheatgrass community pastures in 1969 and 1973 (table 1). Cheatgrass increased, while the forbs, Russian thistle and tansy mustard, declined sharply, although the presence and frequency of the latter two are highly seasonal.

Cover, frequency, and standing crop for the needle-and-thread grass community and the adjacent sagebrush community were estimated in 1973. These values are given in table 2 for comparison with the cheatgrass type (table 1).

Table 1.--*Percent frequency of plant species found in the cheatgrass* [illegible] *and 1973*[1]

[illegible]	1969	1973
GRASSES:		
Streambank wheatgrass	[illegible]	24.6
Cheatgrass	95.0	100.0
Sandberg's bluegrass	42.8	40.0
Bottlebrush squirreltail	[illegible]	.0
FORBS:		
Sego lily	[illegible]	[illegible]
Tansy mustard	59.5	11.4
Prickly lettuce	.0	[illegible]
MacDougal lomatium	[illegible]	[illegible]
Longleaf phlox	1.0	1.2
Russian thistle	96.2	.0

[1] Based on 200 permanent plots (138 in^2, 890 cm^2) in each of two nongrazed pastures.

Table 2.--*Cover, frequency, and standing crop by species in needle-and-thread grass an in the sagebrush communities, Saylor Creek Experimental Range, 1973.*

	Grassland Community			Sagebrush Community		
	Cover	Frequency	Standing crop	Cover	Frequency	Standing crop
	Percent	*Percent*	*kg/ha*	*Percent*	*Percent*	*kg/ha*
SHRUBS:						
Basin big sagebrush						
Leaves						157
Flowers						8
Flower stalks						10
twigs <1 cm						248
Twigs >1 cm						2,304
Deadwood on plants						270
Litter						1517
				[1]28.4		[2]2,997
GRASSES:						
Cheatgrass	57.0	100	530	51.7	100	422
Indian ricegrass	[3] +	+	+			
Sandberg's bluegrass	17.8	72	144	6.8	49	47
Bottlebrush squirreltail	3.2	15	181	1.2	8	12
Needle-and-thread grass	15.6	53	270	10.0	43	255
Thurber's needle grass	.2	1	6	1.7	6	64
			1,131			802
FORBS:						
Low pussytoes				.5	20	11
Beckwith's milk vetch				4.9	11	1
Specklepod locoweed	+	+	+	1.5	3	16
Pursh locoweed	.5	2	+	+	+	+
Sego lily	+	+	+	+	+	+
Northwestern paintbrush				+	+	+
Tapertip hawksbeard	.5	2	10	.5	2	24
Western hawksbeard				+	+	+
Low fleabane				+	+	+
Oval-leaved buckwheat	+	+	+	+	+	+
MacDougal lomatium				1.2	18	4
Nineleaf lomatium				+	+	+
Hood's phlox	+	+	+	+	+	+
Longleaf phlox	1.0	10	12	4.2	44	54
			22			110
TOTAL STANDING CROP			1,153			3,915

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[1] Line interception

[2] Does not include litter weight

[3] Present in macroplot

Table 3.--*Actual and predicted range forage production (95 percent cheatgrass). Yield data at Saylor Creek Experimental Range were taken about June 15 each year. Prediction equation based on the 1961 through 1968 data.*

Year[1]	Actual yield ± Sx̄		Predicted yield[2]
	[illegible]	[illegible]	[illegible]
1961	239 ± 30	268 ± 34	266
1962	505 ± 51	566 ± 57	568
1963	654 ± 49	734 ± 55	728
1964	443 ± 65	497 ± 73	490
1965	491 ± 87	550 ± 98	541
1966	598 ± 110	670 ± 123	677
1967	204 ± 30	229 ± 34	230
1968	103 ± 15	115 ± 17	110
lean	405	453	454
975	545 ± 50	611 ± 56	-97
976	924 ± 56	1,036 ± 63	250
lean	734	824	

[1] For 1961 through 1968 the forage was harvested from a nongrazed pasture, hile the harvests in 1975 and 1976 were from grazed pastures.

[2] Predicted yield = -1,656 + 7.5 (Apr. ppt.) + 80.9 (April mean temp.) - 8.1 (Feb. mean temp.) + 70.8 (May mean temp.) + 1.5 (May ppt.) where recipitation (ppt.) and temperature (temp.) are in millimeters and degrees elsius, respectively.

Forage yield fluctuations on cheatgrass range are well known. Table 3 gives the orage production (mainly cheatgrass) for the years 1961 through 1968, taken from an rea that was not grazed for the entire period. June 15 forage yields during that eriod were highly predictable using a stepwise multiple regression analysis. Fifty-wo percent of the variation in yield was related to April precipitation and April emperature. Ninety-nine percent of the variation in yield was predicted by the quation:

$$Y = -1656 + 7.5 \text{ (Apr. ppt.)} + 80.9 \text{ (Apr. mean temp.)} - 28.1$$

$$\text{(Feb. mean temp.)} + 70.8 \text{ (May mean temp.)} + 1.5 \text{ (May ppt.)}$$

The $R^2 = 0.999$. Yield, precipitation, and temperature are in kilograms dry matter er hectare, millimeters, and degrees Celcius, respectively. Climatic data for Glenns erry, Idaho, were used in the regression analysis.

Murray has observed that moderate grazing of cheatgrass range from year to year stimulates forage production when compared to nonuse. This is substantiated by the fact that the 1975 and 1976 yields from grazed pastures (table 3) were greater than those predicted by the equation. Nonuse for a long period in the absence of fire causes a litter buildup, which may interfere with cheatgrass germination and seedling establishment.

Soils at the experimental range were developed on gently, undulating topography, from Black Mesa gravels and aeolian sources (Malde and Powers 1962). The underlying rock is basalt and has not influenced soil development.

The soils are considered to be in the Minidoka silt loam series, a member of the coarse silty, mixed, mesic Xerollic Durorthid family. Appendix II gives descriptions of the soils for the needle-and-thread grass and sagebrush sites.

Throughout the range, some small areas termed "slick-spots" are present (Rasmusse and others 1972). These soils have a strongly developed B2 horizon that contains larg amounts of exchangeable sodium. Weakly developed "slick-spots" are only noticeable during late May and June when cheatgrass is drying. Within these spots, cheatgrass will turn purple 2 to 3 weeks before the surrounding plants. Also, in many instances, cattle will graze the spot completely to the soil surface, while the surrounding grass appears little used. The reason for this grazing behavior is unknown; perhaps the stressed plants have a higher sugar and/or salt concentration than do plants on the adjacent soils.

METHODS AND PROCEDURES

Field Procedures

Forage phenology data were obtained from field observations made from 1962 through 1968. A variety of techniques, including line intercept, canopy coverage, and permanen circular plots, were used to determine species cover and frequency. Rectangular plots, 7.9 by 19.7 inches (20 by 50 cm), were clipped during the full flower stage to determin standing crops of grasses and forbs (fig. 2), while 236 by 394 inches (6 by 10 m) plots were used to determine the standing crop of basin big sagebrush.

A fertilizer trial, a minor part of the total study, was initiated to determine the effects of added N and P on forage dry matter yield, protein, and mineral concentrations. Cheatgrass plots were fertilized with 0, 40, 80, 120, 160, or 200 lb N per acre (1 lb/acre equivalent to 1.12 kg/ha). Needle-and-thread plots were fertilized with both N and P applied at 40, 80, or 120 lb N or P per acre in all combinations. The N as ammonium nitrate, and P as treble superphosphate, were applied in September 1964 with four replications. All fertilizers were surface-applied. The cheatgrass plots were harvested in mid-June 1965, the needle-and-thread plots were harvested in mid-June 1965 and 1966, and the forage was separated by species.

Figure 5.--[illegible]

Forage dry matter production above 1/2 inch [illegible] by clipping 30 plots 20 inches (51 cm) by 15 feet (4.6 m) except in 1975 and 1976 when 200 randomly located 1-ft^2 (929-cm^2) plots were clipped. Plant material for chemical and forage quality characterization was harvested periodically (at 1/2-inch stubble height) from random clones in the same nongrazed pasture between mid-March and November during the 1962 through 1968 period. Plant material was ovendried 24 to 48 hours at 158° F (70° C) and ground to pass a 40-mesh screen. Forage moisture content was determined on some samples as the water lost by drying at 158° F (70° C) for 24 to 48 hours, divided by dry matter content.

Gravimetric soil moisture content was determined on triplicated soil core samples taken monthly from 1961 through 1968. Additional soil samples for chemical and bulk density analysis were taken from the side of soil pits dug in the cheatgrass, needle-and-thread grass, and sagebrush communities. Samples for chemical and textural analyses were air dried and passed through a 2-mm screen. Bulk density cores were ovendried for 24 hours at 220° F (105° C) and weighed. Soil descriptions follow the standard Soil Conservation Service procedures and terminology.

Forage Analyses

Total nitrogen (N), with the salicylic acid modification for N-N and N-O linkages, was determined by semi-microKjeldahl procedures. Nitric-perchloric acid (3:1) digestion of forage samples preceded analysis for phosphorus (P), sulfur (S), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), zinc (Zn), manganese (Mn), copper (Cu), and iron (Fe). Phosphorus was estimated colorimetrically following the ammonium molybdate-tannous chloride procedures. Sulfur content was determined by a modification of the turbidimetric procedure. All other elements were estimated by atomic absorption spectrophotometry. A standard plant sample that had been analyzed in several other laboratories was used as a check on procedures.

Forage samples were also analyzed for neutral-detergent fiber (NDF), NDF-ash, digestible cell wall (DCW), DCW-ash free, and true dry matter digestibility (TDDM) following the procedures specified by Goering and Van Soest (1970). Rumen fluid inoculum was obtained from a donor cow maintained on a timothy (*Phleum pratense*) grass-hay diet.

Soil Analyses

Soil organic N was determined on finely ground (100-mesh) soil by microKjeldahl procedures. Phosphorus was determined by extracting 5 g soil with 100 ml of sodium bicarbonate (pH 8.5), filtering, and using an ammonium molybdate-stannous chloride procedure to develop the blue color (Olsen and Dean 1965). Sulfate sulfur (SO_4-S) concentrations were obtained following the procedure outlined by Bardsley and Lancaster (1965).

Soluble and exchangeable sodium and potassium were extracted with 1 *N* ammonium acetate (pH 7.0 at a ratio of 5 g soil to 100 ml extracting solution). After shaking for 2 hours, the solution was filtered under suction and Na and K were determined by flame photometry.

Zinc, Mn, Cu, and Fe concentrations were determined by extracting 10 g soil with 20 ml diethylenetriamine pentaacetic acid (DTPA) extracting solution. The extracting solution contained 0.005 *M* DTPA, 0.01 *M* calcium chloride, and 0.1 *M* triethanolamine (TEA) adjusted to pH 7.30 with glacial acetic acid. After filtering, the extracts were analyzed by atomic absorption spectrophotometry (Lindsay and Norvell 1969; Follett and Lindsay 1970). Soil pH was determined on a 1:1 soil:distilled water paste, using a glass electrode.

Calcium carbonate equivalents were determined by acid neutralization (Allison and Moodie 1965). The soils were not analyzed for Ca and Mg, because of the high concentrations of calcium-magnesium carbonate in the profile which, upon extraction with ammonium acetate, yield erroneously high values (Heald 1965) although Mg content was determined on a 1 *N* ammonium acetate extract of the surface soil from the cheatgrass community.

Soil moisture content at the three-tenths and 15-bar tension was determined by pressure plate apparatus.

Statistical Analyses

Seasonal trends in soil water concentrations were calculated using a 2-factor Fourier analysis (Bliss 1958). Linear and curvilinear regression techniques were used to summarize forage water, forage mineral concentrations, and forage quality data. All forage mineral and nutritive quality data were fit to each of the following curve forms: $a + b/x$, ax^{bx}, $a + bx$, ae^{bx}, $x/(a + bx)$, $1/(a + bx)$ and $a + bx + cx^2$. The curve form selected was the one yielding the largest sum of r^2 values for the seven species tested.

Animal Weight-Gain Responses

Hereford and Angus beef cattle, or crosses of these breeds, were provided by local livestockmen. Yearling cattle weight-gain responses to various stocking intensities were determined by the "put-and-take" method. Other yearling and cow-calf weight-gain responses to season-long grazing of moderate intensity were also determined. Animals grazed within 0.6 mi (1 km) of water and were weighed at periodic intervals (generally 28 days) following an overnight shrink without feed or water.

RESULTS AND DISCUSSION

Soil Moisture

Monthly precipitation for 1961 through 1968 is shown in conjunction with soil oisture at Saylor Creek Experimental Range in the 0- to 12-inch (0- to 30-cm) and 2- to 24-inch (30- to 60-cm) depths (fig. 3).

Because most of the precipitation falls as snow or rain in winter and spring, lants generally mature by early to midsummer. Shallow-rooted plants, such as cheatrass and bluegrass, mature before the deeper rooted species, which is reflected in orage moisture concentrations (table 4) and is related to the characteristic soil oisture patterns illustrated in figure 4. This analysis, representing 9 years of ata, leads to highly predictable soil moisture values for the various soil depths and ndicates a lag in soil moisture depletion with increasing depth during spring and ummer months that explains the differential curing between shallow- and deep-rooted pecies.

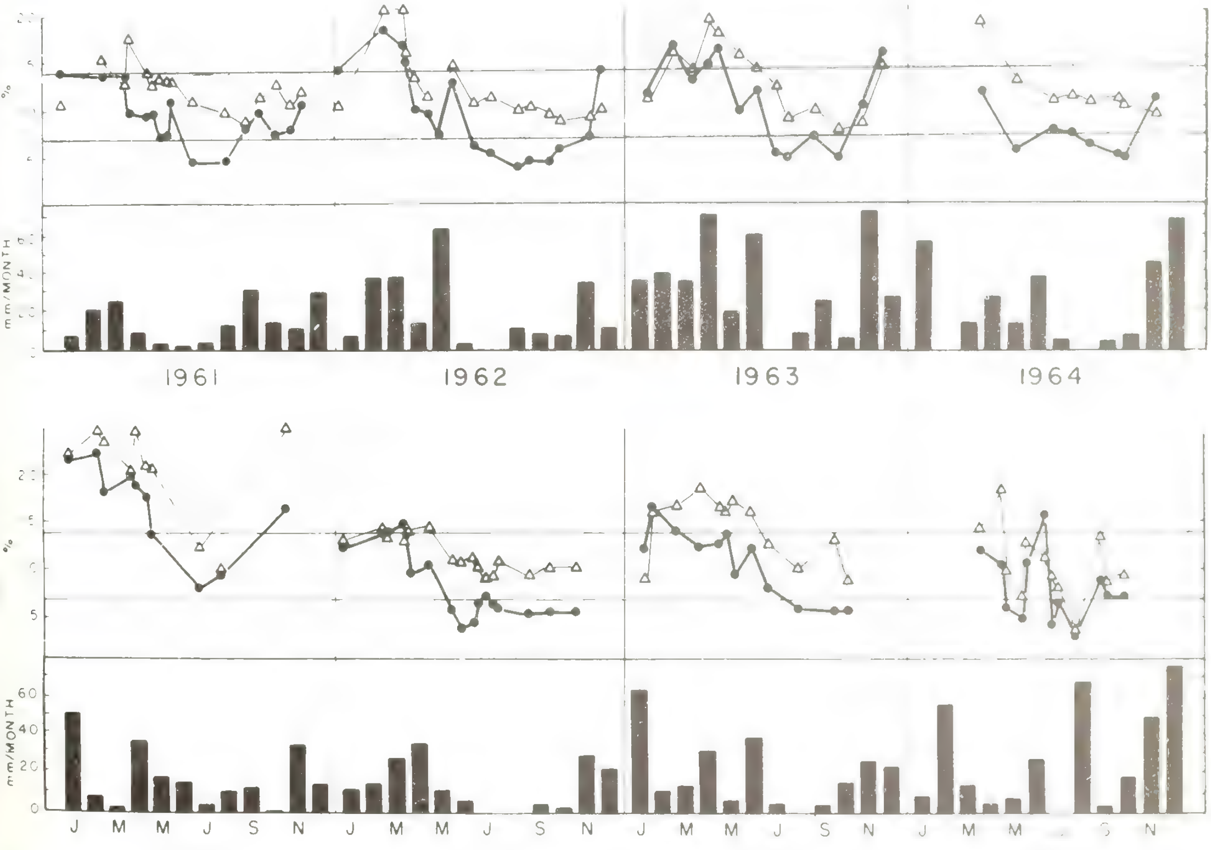
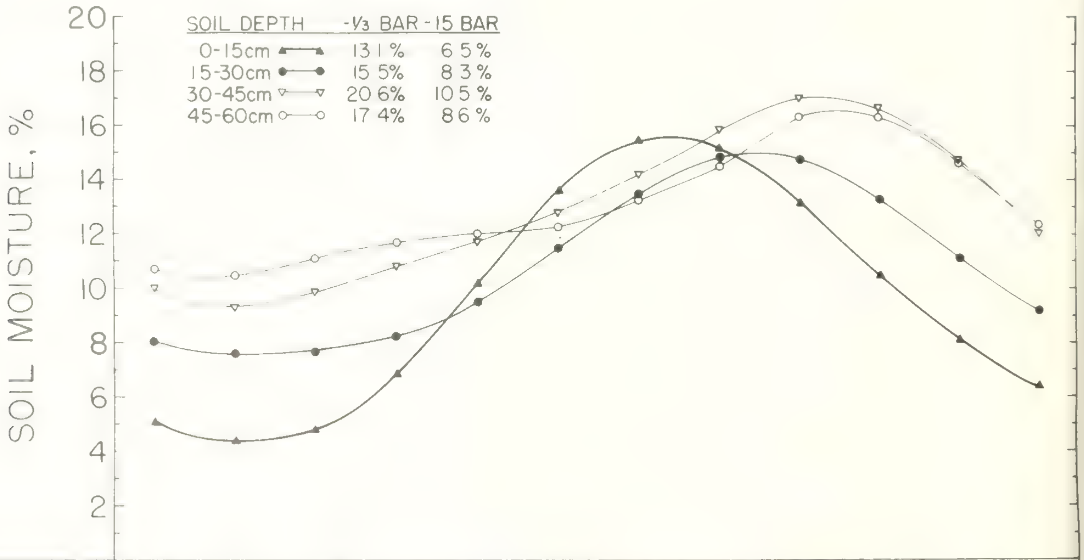


Figure 3.--Trends in soil moisture for the 0- to 12-inch (0- to 30-cm) and 12- to 24-inch (30- to 60-cm) depths for the years 1961 through 1968 in relation to monthly precipitation. The -0.3 bar water content is 13.5 percent and the -15 bar water content is 7 percent (W/W).

Table 4.--*Regression of forage moisture content ($Y = ((\text{Wet Weight} - \text{dry weight})/\text{dry weight}) 100$) against date (X) and correlation values for each of seven species collected on periodic dates for 5 years of a 7-year period and the predicted $\hat{Y}$ values for each of four dates.*

Species	Regression-correlation	Collection date 4/15	5/15	6/15	7/15
		Predicted forage moisture, $\hat{Y}$			
Desert Wheatgrass	$Y = 380 - 1.51X$, $r^2 = 0.75$	220	175	128	83
Streambank wheatgrass	$Y = 317 - 1.23X$, $r^2 = .70$	187	150	112	75
Cheatgrass	$Y = 669 - 3.52X$, $r^2 - .85$	296	190	81	0
Basin wildrye	$Y = 524 - 2.13X$, $r^2 = .87$	298	234	168	104
Sandberg's bluegrass	$Y = 348 - 1.70X$, $r^2 = .72$	168	117	64	13
Bottlebrush squirreltail	$Y = 455 - 2.05X$, $r^2 = .82$	238	176	113	51
Needle-and-thread grass	$Y = 265 - 1.05X$, $r^2 = .61$	154	122	90	58



		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
0-15cm	MEAN	4.74	4.28	5.33	6.42	10.06	13.82	15.48	14.97	13.13	10.70	7.84	6.79
	$S\bar{x}$	0.63	0.73	1.05	1.08	1.06	0.85	1.10	0.80	0.68	0.93	1.05	[illegible]
15-30cm	MEAN	7.99	7.33	7.78	8.18	9.57	11.62	13.06	14.96	15.10	13.22	10.49	9.81
	$S\bar{x}$	0.57	0.68	0.93	1.20	1.01	0.78	0.77	0.95	0.87	1.04	1.01	0.69
30-45cm	MEAN	10.12	9.58	10.42	10.72	11.51	12.39	13.92	16.54	17.33	17.07	13.82	12.02
	$S\bar{x}$	0.76	0.53	0.75	1.38	1.29	1.06	1.17	1.14	0.96	0.82	0.99	0.76
45-60cm	MEAN	10.88	10.11	11.32	11.56	11.66	12.42	13.34	15.16	15.94	16.50	13.92	13.01
	$S\bar{x}$	0.37	0.45	1.00	1.70	1.49	0.97	1.13	1.25	1.39	1.03	0.99	0.63
MONTH		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN

Figure 4.--*Trend in soil moisture at four depths at Saylor Creek Experimental Range. Mean monthly soil moisture percentage and standard error of the mean calculated from 9 years' data (1961 through 1969). The 1/3 and 15-atmosphere values for each depth given in table at top left. Data for soil moisture curves were calculated from 9 years' data using a two-factor Fourier analysis (Bliss 1958).*

Soil Mineral Availability

Mineral composition of soil has an important bearing on soil fertility and plant chemical composition. Soils having a high proportion of minerals resistant to weathering, like granite quartz, are generally infertile. At Saylor Creek, the soils are derived from sedimentary and aeolian sources and are comparatively productive.

Plants with a wide and deep root distribution in the soil profile probably have a greater chance for ion uptake than those with narrow or shallow root distributions. Most roots were concentrated in the 0- to 16-inch (0- to 40-cm) zone in cheatgrass, needle-and-thread grass, and sagebrush-grass communities. In the first two communities, few roots were found below 16 inches (40 cm), but in the sagebrush-grass community roots were found in relatively greater abundance below 16 inches (40 cm).

Throughout the 32- to 55-inch (80- to 140-cm) zone at the needle-and-thread grass sites, decaying sagebrush roots were found upon fragments of caliche. Apparently, some sagebrush roots are unable to find their way through the caliche zone even during periods of high moisture.

Soil characteristics for the needle-and-thread grass, sagebrush-grass, and cheatgrass sites are given in table 5. Organic N, K, Mn, and Fe concentrations were greater near the surface and tended to decrease with depth. At the needle-and-thread grass site, the organic N increased in the 32- to 55-inch (80- to 140-cm) zone because of the decaying sagebrush roots. At the cheatgrass site, organic nitrogen began to increase at about 8 inches (20 cm). The levels of organic N were comparable to those found in a Minidoka silt loam soil from Canyon County, Idaho (Priest and others 1972).

Phosphorus, Zn, and Cu distributions were somewhat variable with depth, but tended to occur in higher concentrations near the surface. Both Na and sulfate-sulfur increased with depth. The higher concentrations of highly mobile Na and sulfate (1,050 and 916 ppm in the 32- to 55-inch (80- to 140-cm) zone) of the needle-and-thread grass site, compared to 450 and 136 ppm at the sagebrush site, might have resulted because deep-rooted sagebrush was removed in 1957 and these ions were leached from the upper profile and accumulated in the 32- to 35-inch (80- to 140-cm) zone of the grass site, but more likely represent some differences in soils between the two sites.

Follett and Lindsay (1970) found that the average DTPA-extractable Zn, Mn, and Fe contents from 37 Colorado soil profiles decreased with depth, while Cu remained relatively uniform with depth. They also found that the range varied from 0.13 to 14.2 ppm for Zn, 1.5 to 160 ppm for Fe, 0.6 to 39.5 ppm for Mn, and 0.14 to 3.68 ppm for Cu. Our values fell within these ranges, averaging toward the lower end of the range.

Some elements are readily leached from plant tissues (Mes 1954) which, with litter accumulation and decay, accounts for the high concentrations in the surface soil. Precipitation collected from under sagebrush plants contained more minerals than that collected from between sagebrush plants (Murray 1975). Part of the increase is probably due to the precipitation washing dust from the plant leaves.

Although plants use N in the ammonium and nitrate forms, little inorganic N can be detected in these soils during the growing season. Consequently, N is measured as organic N and the levels are assumed to indicate the potential availability of N. Stevenson and Wagner (1970) state that organic N consists mainly of (1) nitrogenous biochemicals synthesized biochemically by micro-organisms living on plant and animal residues, and (2) products formed by secondary synthesis reactions which bear no resemblance to any substances in plant and animal tissues (humic and fulvic acids). These products are eventually transformed into ammonium and nitrate--N. Moist Saylor Creek surface soils incubated for 10 weeks in the dark produced 16 ppm nitrate-N, and when alfalfa was added as an energy source to soil, it produced 58 ppm nitrate-N. Fertilization with N increases plant yields at Saylor Creek, thus indicating that N is limiting.

Table 5.--*Soil characteristics of the needle-and-thread grass, sagebrush-grass, and cheatgrass sites at the Saylor Creek Experimental Range (1972)*

NEEDLE-AND-THREAD GRASS SITE

NE.1/4, SE.1/4, sec. 17, T.6S., R.9E., Boise Meridian

Depth (cm)	pH	$CaCO_3$	N	K	P	SO_4-S	Na	Zn	Mn	Cu	Fe	Bulk density	15 A
		-----*Percent*	------		----------	----------	--*Ppm*--	----------	----------	----------	----------	g/cm^3	*Perce*
0-10	8.2	3.8	0.106	0.040	2.8	5	12	0.9	7.6	1.2	5.3	1.32	7.7
10-20	8.3	[illegible]	.074	.028	2.2	T	12	1.0	6.1	1.2	5.3	1.43	8.3
20-30	8.4	[illegible]	.065	.022	2.3	T	14	.4	4.5	1.1	3.7	1.66	7.8
30-40	8.3	24.1	.066	.015	.9	T	19	.3	5.1	.9	3.5	1.70	8.4
40-80	[illegible]	43.4	.061	.009	1.5	7	152	.4	4.0	.5	2.6	1.68	9.5
80-140	8.3	36.0	.080	.020	3.0	916	1,050	.5	3.5	.4	2.0	1.64	

SAGEBRUSH-GRASS SITE

SE.1/4, NW.1/4, sec. 17, T.6S., R.9E., Boise, Meridian

Depth (cm)	pH	$CaCO_3$	N	K	P	SO_4-S	Na	Zn	Mn	Cu	Fe	Bulk density	15 A
		-----*Percent*	------		----------	----------	--*Ppm*--	----------	----------	----------	----------	g/cm^3	*Perce*
0-10	7.9	3.0	0.089	0.051	4.8	5	8	1.1	13.9	1.1	12.0	1.33	7.3
10-20	8.2	9.0	.082	.044	2.3	T	10	.4	10.2	1.6	7.0	1.45	7.8
20-30	8.4	[illegible]	.044	.032	.6	T	8	.4	8.4	1.8	4.7	1.50	8.9
30-40	8.4	19.7	.070	.025	1.0	T	10	.4	6.5	.8	4.7	1.54	9.2
40-80	8.6	24.7	.039	.025	1.5	1	17	.4	4.9	1.0	4.5	1.82	7.4
80-140	8.8	57.3	.041	.030	2.4	136	450	.5	2.4	.5	2.7	1.71	10.9

CHEATGRASS SITE

Center NE.1/4, sec. 28, T.6S., R.9E., Boise Meridian

Depth (cm)	pH	Mg	N	K	Na	Sand	Silt	Clay	C.E.C.
		----------*Percent*	----------		*Ppm*	--------	*Percent*	--------	*Meq./100 g*
0-5	[illegible]	0.010	0.093	0.055	18	42	44	14	11.6
5-10	7.8		.067			43	41	16	
10-15	7.9	.015	.066	.044	18	43	41	16	12.8
15-20	7.9		.068			43	41	16	
20-25	8.0	.018	.074	.035	21	44	39	17	10.1
25-30	8.0		.083			43	40	17	
30-36	8.1	.021	.090	.032	20	43	38	18	11.3
36-41	8.2		.088			43	38	18	
41-46	8.2	.022	.095	.022	23	48	38	14	10.7
46-51	8.3		.063			54	34	12	

[illegible] and others (1955) found that [illegible] availability is governed by the carbon dioxide and pH of the soil. They show that P availability is reduced by the presence of calcium carbonate. Truog (1946) noted that between pH 6.5 and 7.5 conditions are most favorable for P availability; between pH 7.5 and 8.5 P availability is reduced; and at pH 8.5 and higher soluble sodium phosphate readily available for plant use would be formed. In the active rooting zone at Saylor Creek, pH values fall between 7.5 and 8.5, and thus P deficiencies could also limit plant growth.

Soil sulfur exists in both organic and inorganic forms. Tabatabai and Bremner (1972) discuss two forms of organic sulfur: (1) organic sulfates containing C-0-S linkages, and (2) S containing amino acids (methionine and cysteine). These forms are broken down to inorganic sulfates by micro-organisms, and it is in this form that plants take up S. The pH of the soil, except under very acid conditions, has little effect on S availability. However, the sulfate ion is mobile and readily leached as evidenced by the needle-and-thread grass site (table 5). It is not known whether the low concentration of S in the 4- to 16-inch (10- to 40-cm) zone is due to plant uptake, leaching, or differences in basic soil chemistry. Sulfate fertilization may be beneficial to plant growth, especially if N fertilization were practiced.

Generally, large quantities of K are found in soils, but most is in unavailable forms. However, the extractable K in Saylor Creek soils appears to be adequate.

Sodium is not known to be essential for plant growth except that certain saltbush species require it (Brownell 1965). Sodium levels in the Saylor Creek soils, within the rooting depth, are not sufficiently high to present a toxicity problem. Data in table 5 indicate that Na is readily transported to the lower depths. "Slick-spot" soils contain larger quantities of Na in the B horizon than normal soils. An examination of a well-developed "slick-spot" profile revealed that the A and B horizons contained 13 and 167 mg Na per 100 grams of soil, respectively. Such soils have only sparse vegetation.

Threshhold levels of extractable (with DTPA) trace minerals above which greater dry matter production will not result for many intensively managed crops on soils of the types at Saylor Creek can be tentatively considered as 1, 1, 5, and 5 ppm for Zn, Cu, Fe, and Mn, respectively. On this rangeland, soil water and perhaps N and S are limiting plant growth, and we would not expect forage growth response to trace mineral additions.

Zinc, Mn, Cu, and Fe availabilities are severely reduced at soil pH levels above 7.5 (Truog 1946). Peech (1941) found that at pH 9.0, nearly all the Zn is fixed. The uptake of Zn decreases with increasing Ca++ levels in soil (Epstein and Stout 1951). However, Wear (1956) has shown that uptake of Zn is controlled by pH and is not a calcium effect.

Zinc, Mn, Cu, and Fe concentrations were determined in alkali sacaton (*Sporobolus wrightii*) growing on sodic soils in Arizona (Bohn and Aba-Husayn 1971). They found that the Zn and Cu concentrations in the plants decreased as the pH of the soil changed from 7.5 to 9.5, but that the Mn and Fe contents increased. They suggested that this could be due to the reducing conditions resulting from [illegible] of these soils. Under our conditions at Saylor Creek, it is likely that the availability of these micronutrients is reduced by the higher pH.

Forage Yield and Mineral Content After Fertilization

The fertilization trial was initiated to determine the effects of added N (as NH_4NO_3) and P (as treble superphosphate) on yield and protein content of grasses within the cheatgrass and needle-and-thread grass communities. We later decided to analyze the same samples for additional nutrients (tables 6 and 7).

Table 6.--*Effects of different N (as NH_4NO_3) fertilization rates on yield and mineral concentrations or ratios of cheatgrass and tansy mustard. Fertilized in September 1964 and harvested in June 1965*

Fertilization rate (lb/ac	(kg/ha))	Yield		N	P	S	Ca	Mg	K	Na	Zn	Mn	Cu	N:S	K / (Ca+
		lb/ac	*(kg/ha)*	- - - - - - -	- - *Percent*	- - - - -	- - - - -	- - - -		- - -	- *Ppm* -	- - -	-		
						CHEATGRASS									
0	(0)	670	(750)	0.45	0.062	0.040	0.280	0.078	0.40	143	18	61	6.1	11.2	0.
40	(45)	1,228	(1,380)	.45	.062	.030	.315	.082	.40	275	16	64	4.1	15.0	.
80	(90)	1,552	(1,740)	.60	.053	.035	.307	.077	.40	137	13	70	3.8	17.1	.
120	(134)	1,667	(1,870)	.83	.075	.048	.408	.100	.45	141	16	78	4.4	17.3	.
160	(179)	2,104	(2,360)	.78	.058	.040	.376	.082	.35	189	16	84	4.2	19.5	.
200	(224)	2,269	(2,540)	.91	.070	.050	.446	.097	.57	208	15	64	3.8	18.2	.
						TANSY MUSTARD									
0	(0)	252	(280)	1.28	.178	.325	.784	.201	1.05	92	16	20	3.6	3.9	.
40	(45)	488	(550)	1.28	.191	.395	1.189	.359	1.10	86	15	12	3.3	3.2	.
80	(90)	330	(370)	1.82	.150	.420	1.544	.390	1.15	62	15	24	3.7	4.3	.
120	(134)	224	(250)	2.26	.182	.430	1.664	.462	1.18	73	18	26	4.8	5.3	.
160	(179)	70	(80)	2.00	.137	.435	1.319	.384	1.02	82	16	16	2.7	4.6	.
200	(224)	288	(320)	1.90	.130	.382	1.291	.340	1.02	164	14	16	2.1	5.0	.

Table 7.--*Mineral composition of selected species in relation to nitrogen and phosphorus fertilization 1 and 2 years after application*[1]

	N	P	S	Ca	Mg	K	Na	Zn	Mn	Cu	N/S
	-------	-------	*Percent*	-------	-------	-------	-------	-------	*Ppm*	-------	-------
Desert wheatgrass (1965)											
Without fertilization	0.94	0.127	0.75	0.264	0.074	1.050	66.0	16.0	38.0	6.7	12.
With fertilization	1.19	.131	.92	.288	.084	.972	65.0	14.8	44.4	7.8	13.
S.E.m	.07	.003	.01	.010	.003	.086	3.0	.5	1.4	.3	.
Desert wheatgrass (1966)											
Without fertilization	1.03	.112	.105	.444	.101	1.040	52.0	11.0	34.0	4.4	9.
With fertilization	1.28	.121	.105	.459	.115	1.090	56.2	12.0	56.9	7.2	12.
S.E.m	.05	.003	.004	.016	.003	.043	1.5	1.1	2.3	1.6	.
Cheatgrass (1965)											
Without fertilization	.46	.068	.030	.337	.088	.350	85.0	19.0	81.0	7.7	15.
With fertilization	.60	.064	.034	.340	.087	.353	119.0	15.2	84.2	7.4	17.
S.E.m	.03	.004	.002	.007	.002	.013	10.0	.9	2.2	.3	.
Sandberg's bluegrass (1965)											
Without fertilization	.92	.078	.072	.569	.121	.180	74.0	17.0	74.0	5.3	12.
With fertilization	1.12	.082	.059	.531	.116	.217	74.8	17.4	66.3	5.7	19.
S.E.m	.04	.002	.002	.010	.002	.006	2.6	.3	2.4	.1	.
Sandberg's bluegrass (1966)											
Without fertilization	1.36	.108	.105	.658	.148	.380	69.0	12.0	67.0	6.1	13.
With fertilization	1.43	.123	.110	.600	.143	.436	68.5	13.2	70.3	5.7	13.
S.E.m	.04	.004	.003	.013	.002	.020	2.1	.3	1.9	.2	.
Needle-and-thread grass (1965)											
Without fertilization	1.18	.140	.136	.684	.166	.920	65.0	16.0	33.0	5.8	8.
With fertilization	1.48	.110	.109	.610	.162	1.048	71.8	15.2	51.6	6.1	13.
S.E.m	.05	.003	.003	.025	.006	.022	4.0	.2	2.7	.1	.
Needle-and-thread grass (1966)											
Without fertilization	1.80	.090	.114	.635	.162	.650	87.0	14.0	73.0	5.8	15.
With fertilization	1.21	.099	.126	.632	.166	.698	74.6	12.6	79.3	5.5	9.
S.E.m	.03	.002	.002	.005	.002	.027	.6	.3	1.5	.1	.

---

[1] Mineral concentrations in nonfertilized forage are compared to those in forage fertilized with 40, 80, or 120 lb/acre N in combination with 0, 40, 80, and 120 lb P/acre. Data within the 40 to 120 lb/acre N or P were not different from each other and were therefore combined and the standard error of the mean (S.E.m) calculated.

Fertilization with N increased cheatgrass dry matter yields from 670 to 2,270 lb per acre (750 to 2,540 kg/ha). Concurrent with a yield increase, the N concentration of the forage also increased from 0.45 to 0.91 percent. Higher N concentrations were found in tansy mustard plants at higher fertilization rates, but yields were erratic.

In cheatgrass, Ca was the only other nutrient that tended to increase with increasing levels of N application. The micronutrients were not influenced by added N. Nitrogen application caused the N:S ratio to become wider, which may reduce forage protein digestibility.

Nitrogen fertilization tended to increase S, Ca, and Mg concentrations in tansy mustard. The stimulation of cheatgrass and the weedy mustard species by N fertilization is caused by their early growth and utilization of available water and plant nutrients. These species would be expected over several seasons to gain a competitive advantage over any desirable perennials that might be present.

On the needle-and-thread grass range, both N and P were applied at rates of 40, 80, and 120 lb per acre (45, 90, and 134 kg/ha) in all combinations in September 1964; applications were replicated four times. The plots were harvested in June 1965 and June 1966 and species were separated. The results are given in table 7. The nonfertilized plots are shown in the table as "without fertilization" and constitute the composite of the four replications. The "with fertilization" data are the mean from all N and P plots without regard to level. The standard error of the mean (S.E.m) was computed from the latter data set and represents the chance of finding the true mean within the values given 67 percent of the time. If it is assumed that the "without fertilization" data have a similar standard error, then one can compare the effect of fertilization on the chemical composition. The data have been interpreted in this light, i.e., effects of at least 40 lb of N plus 0, 40, 80, or 120 lb of P per acre, compared to nonfertilized forage.

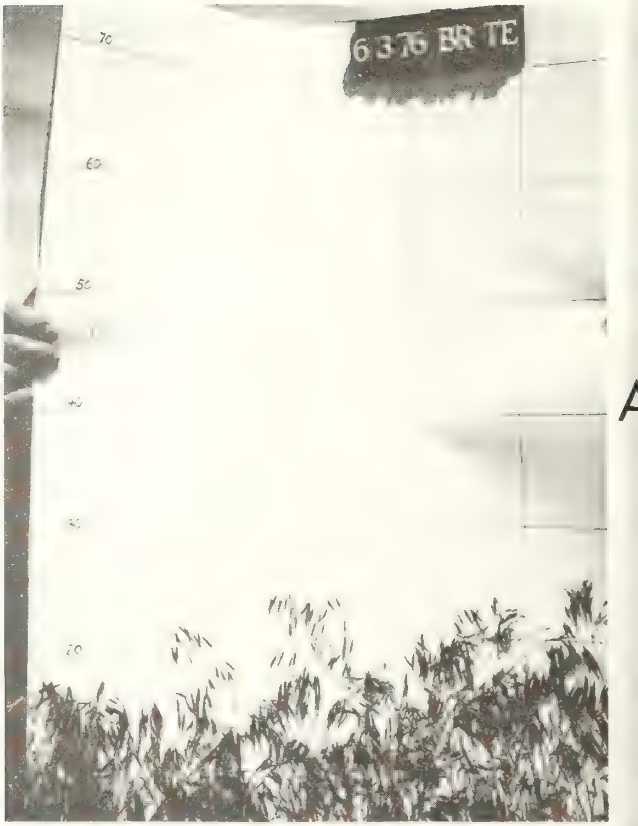
Fertilization increased the N content of desert wheatgrass, cheatgrass, bluegrass, and needle-and-thread grass in 1965, and of all species except needle-and-thread grass in 1966. From the original data, it appeared that P applications had little effect on increasing N content.

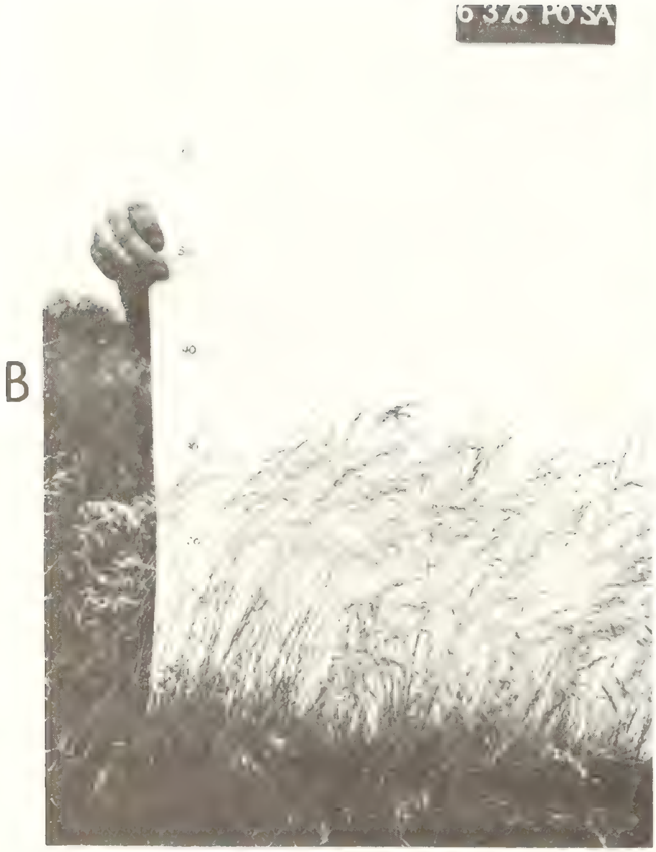
Fertilization did not greatly increase plant tissue levels of other nutrients, although there was a tendency for P to increase in some plants the second year following fertilization. It is possible that P was just becoming available. Phosphorus applications at higher N levels tended to increase the P content in bluegrass and wheatgrass in both 1965 and 1966, but not in cheatgrass nor needle-and-thread grass. Sulfur increased considerably in wheatgrass 1 year after fertilization, but no increase was detected in the second year. In cheatgrass, Na uptake increased in 1965. Manganese levels were higher in needle-and-thread grass in 1965 and in desert wheatgrass in 1966 due to fertilization. The erratic nature of these results indicates that fertilization with N and P cannot be relied upon to increase levels of nutrients other than N and possibly P.

Forage Nutritive Quality on Unfertilized Rangeland

Photographs of the seven grasses and the patterns of plant development for the seven grass species at Saylor Creek are shown in figures 5 and 6, respectively. The variations from year to year when the different stages occur explains some of the variations in chemical content. In addition, variations in chemical content also occur as the result of factors that influence availability and uptake.

We plotted mineral concentrations, digestibility components, and mineral ratios against dates in a series of graphs. When the respective r^2 value is significant, the equation for the least squares fit of the data is given.





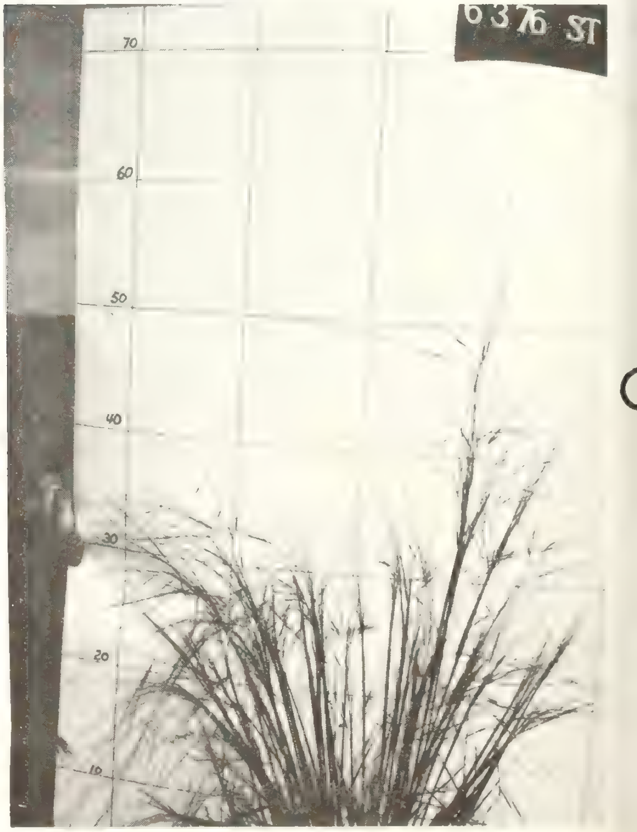
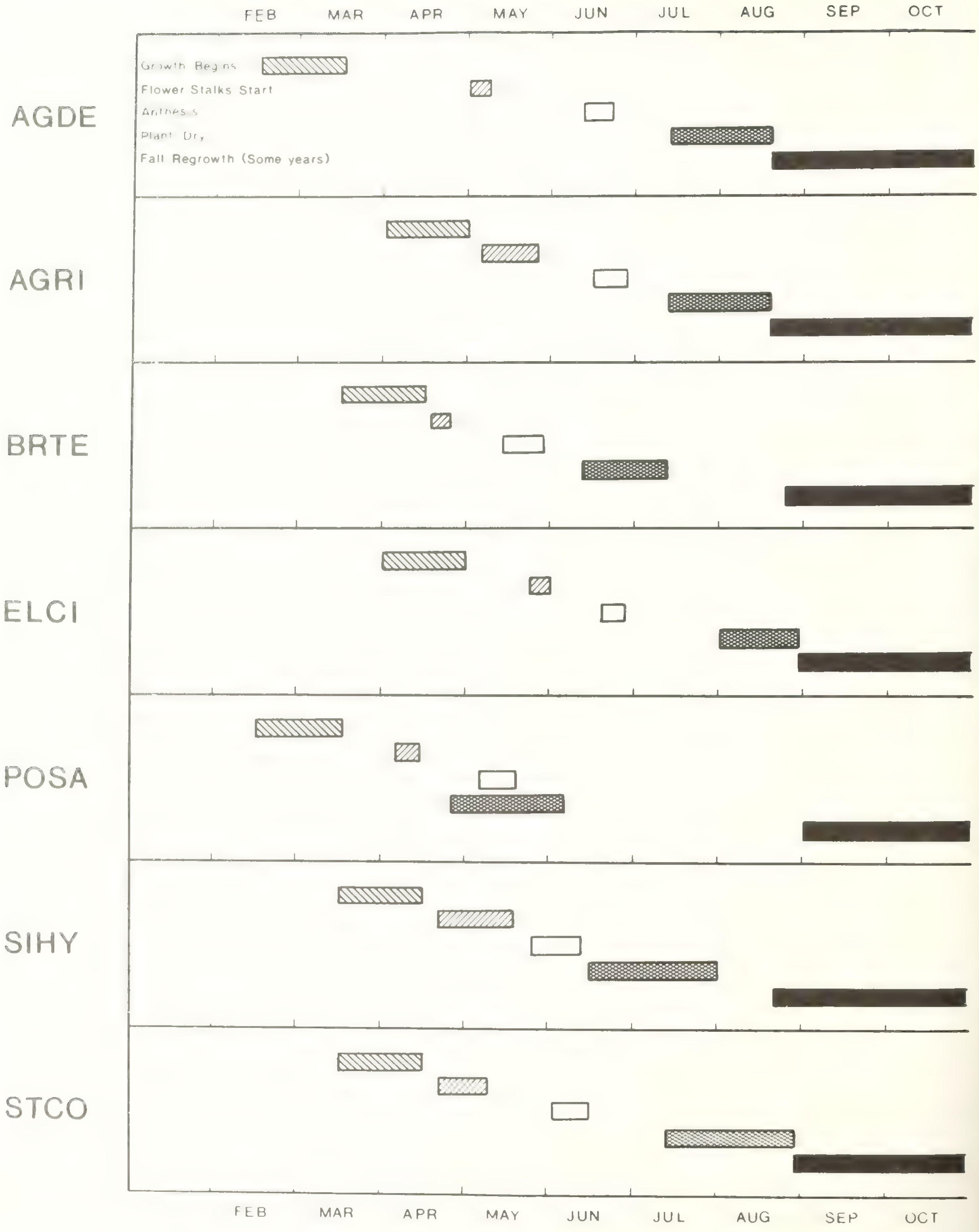


Figure 5.--Photographs of the seven intensively studied grass species: A. cheatgrass; B. Sandberg's bluegrass; C. needle-and-thread grass; D. bottlebrush squirreltail; E. desert wheatgrass; F; streambank wheatgrass; and G. basin wildrye grass. Photos were taken in midsummer 1976. Height is measured in centimeters. Backdrop grid is in decimeters.

D

E

G



[illegible] Plant development of seven grass species. The beginning of the bar represen the earliest date and the end of the bar the latest date at which the stage occurred. (Data taken at Saylor Creek Experimental Range over the period 1960 to 1969).

Most of these figures show an exponential decay in mineral concentrations. T results because (1) plants tend to accumulate most of the minerals early in the se while subsequent dry matter accumulation is predominantly carbon compounds, and (there is a later loss of mineral-rich leaves and seed heads. Also, as the season vances, soil dries to greater depths and the moisture found at progressively lower depths is used to support top growth and root elongation, plant transpiration, and medium for soil mineral diffusion. The rate of mineral uptake may, as the season gresses, be reduced during soil drying because of reduced mineral diffusion rates to t roots and because mineral availability generally decreases with increasing soil depth (fig. 4, table 5).

Animal preference for various plant species is closely related to stage of plant development. Our observations of cattle grazing on cheatgrass range show a characteristic pattern. Very early in the spring when cheatgrass is short, cattle graze almost entirely upon the bluegrass and wheatgrass when these species are present. As cheatgrass becomes more available, the animals graze it heavily. Cattle tend to graze only the lower leaves of floral tillers. If the grazing pressure is sufficiently heavy, they eat the entire plant. Bluegrass is usually avoided when the plant is in anthesis. Although cheatgrass is utilized throughout the season from April through November, other plants are definitely preferred when cheatgrass has dried.

Early grazing and precipitation coming in late May and June favor the development of Russian thistle. Under these conditions, considerable thistle will be present on cheatgrass range. This species is heavily utilized throughout the summer and early fall before the plant becomes dry and spiny (fig. 7B). It provides a source of protein when other species are normally very low in protein.

Figure 7.--Forbs, such as goatsbeard (A) and especially Russian thistle (B), ar
[illegible]
about 20 inches (50 cm) in height.

B

Western hawksbeard and goats-beard are found in some years on this range, and the initial growth in the late spring and regrowth in late summer are readily eaten by cattle. Like Russian thistle, they are considered good forage, but contribute little to total dietary intake.

On cheatgrass range, generally two types of operations exist. The principal type on most of the range is a cow-calf system, but some operators run only yearlings. An abbreviated list of nutrient requirements is given in table 8, and nutrient concentrations are discussed in relation to animal requirements when known. Additional information on animal requirements will be found in the National Academy of Science publicatio (NAS-NRC 1976) from which table 8 data are taken. The following information considers total mineral analysis in the clipped forage and does not evaluate animal preference for given species or plant parts.

Nitrogen

Total N concentrations (fig. 8) in the seven grass species were greater than 3 percent (approx. 19 percent protein) in April, but declined rapidly, and by August all species contained less than 1 percent N (6.2 percent crude protein). Desert wheatgrass in one March sample had more than 4 percent N, as did cheatgrass in an April sample. However, cheatgrass, an annual, dries rapidly, and many of the samples taken after June contained less than 1 percent N. In spite of the fact that leaves of Sandberg's bluegrass dry comparatively early, the N content remained higher than that of cheatgrass.

Lactating cows require at least 9.2 percent protein (1.47 percent N) in the daily ration to maintain body weight. Thus, a crude protein supplementation program should be considered for lactating cows grazing cheatgrass after mid-June. Growing steers

Table 8.--*Nutrient requirements for beef cattle* [illegible]

Body weight	Average daily gain	Daily dry matter/animal	Total protein	Digestible protein	Ca	P
--------	kg	--------	--------	percent	--------	--------
			GROWING STEERS			
200	0.00	3.5	8.5	4.8	0.18	0.18
	.50	5.8	9.9	6.0	.24	.22
	.70	5.7	10.8	6.8	.32	.28
400	.00	5.9	8.5	4.8	.18	.18
	1.00	9.4	5.7	5.7	.22	.21
			GROWING HEIFERS			
200	.00	3.5	8.5	4.9	.18	.18
	.50	6.0	9.6	5.8	.23	.22
	.70	6.0	10.2	6.5	.30	.27
400	.00	5.9	8.5	4.8	.18	.18
	.50	8.5	8.8	5.1	.18	.18
	.70	8.7	9.0	5.3	.18	.18
			DRY PREGNANT MATURE COWS			
400	.4	6.1-7.5	5.9	2.8	.18	.18
500	.4	7.2-8.6	5.9	2.8	.18	.18
600	.4	8.3-9.7	5.9	2.8	.18	.18
			LACTATING COWS			
400	-	8.8	9.2	5.4	.28	.28
500	-	9.8	9.2	5.4	.28	.28

Estimated requirements for all animals:

Mg - 12 to 30 mg/kg of body wt/day
S - 0.1 percent of ration dry matter
Mn - 1 to 10 mg/kg of ration dry matter
Fe - 80 to 100 mg/kg of ration dry matter
Na - 0.05 percent of ration dry matter
K - 0.6-0.8 percent of ration dry matter
Zn - 20 to 30 mg/kg of ration dry matter
Cu - 4 mg/kg of ration dry matter when feed is low in Mo and sulfate

and heifers weighing 660 lb (300 kg) and gaining 2.0 lb per day (0.9 kg/day) require 10.0 percent protein (1.6 percent N) in the ration. The same animals, just to maintain their weight, require 8.6 percent protein (1.4 percent N) in the ration (NAS-NRC 1976). The N curves show that the maintenance level for growing steers and heifers is reached in June and July for most species, and after July N is deficient for maintaining yearlings and lactating cows.

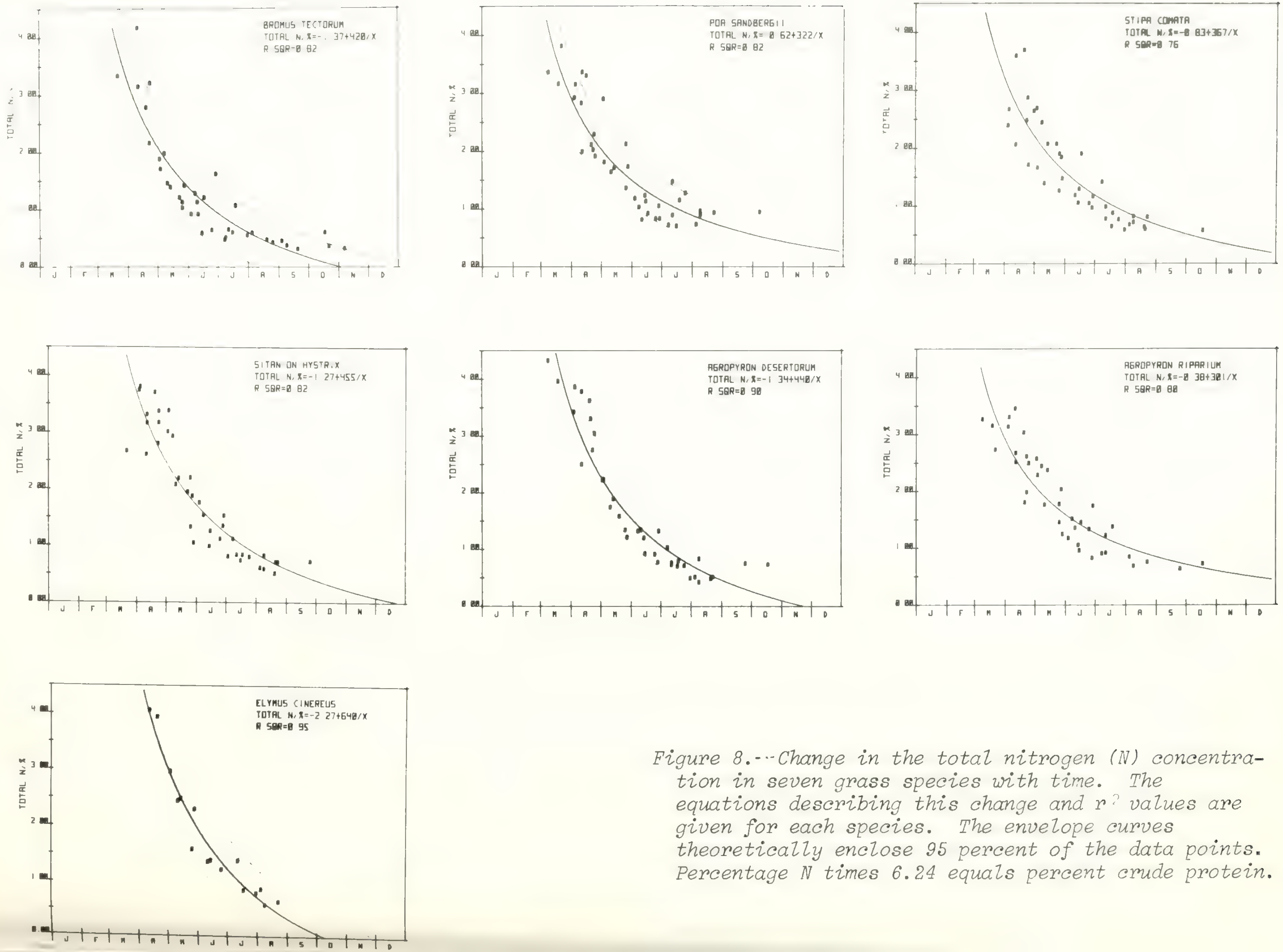


Figure 8.--Change in the total nitrogen (N) concentration in seven grass species with time. The equations describing this change and r^2 *values are given for each species. The envelope curves theoretically enclose 95 percent of the data points. Percentage N times 6.24 equals percent crude protein.*

Phosphorus

Total plant P (fig. 9) concentration trends follow a pattern very similar to total N, but values are lower by a factor of approximately 10. NAS-NRC lists a requirement of 0.18 percent P in the forage for maintenance of growing steers and heifers, and higher concentrations are needed if animals are fed to gain weight. The same concentration is required for dry pregnant cows, but cows with calves require forage containing 0.28 percent P.

In most species and in most years, the P values we found were below the recommended values by the end of June. Robertson and Torell (1958), in northeastern Nevada, found that cheatgrass, basin wildrye, Sandberg's bluegrass, and needle-and-thread grass had phosphorus contents of 0.27, 0.09, 0.11, and 0.17 percent in the mature stage, respectively. Other workers have also found similar low contents after maturity.

Calcium and Ca:P Ratio

A better measure of the P requirement is the Ca:P (percent/percent) ratio. The ratios should be 2:1 under normal circumstances, but can be as wide as 7:1 when sufficient vitamin D is present.

Calcium concentration values (fig. 10) for the seven species, when plotted over time, were extremely erratic except for cheatgrass. As a consequence, the Ca:P ratios were somewhat erratic, but did show an increase over time (fig. 11). Surprisingly, cheatgrass maintained a ratio of less than 7:1 through October. Desert wheatgrass maintained the lowest ratio of all species. The other species exceeded the 7:1 ratio before the end of the grazing season in October.

In a 112-day study on Saylor Creek range, yearling cattle supplemented with a trace mineral salt only versus trace mineral salt and monosodium phosphate at a ratio of 2:1 gained similarly, indicating phosphorus was not deficient (Olsen 1971). Lactating cows, on the other hand, have a higher P requirement and may respond to P supplementation.

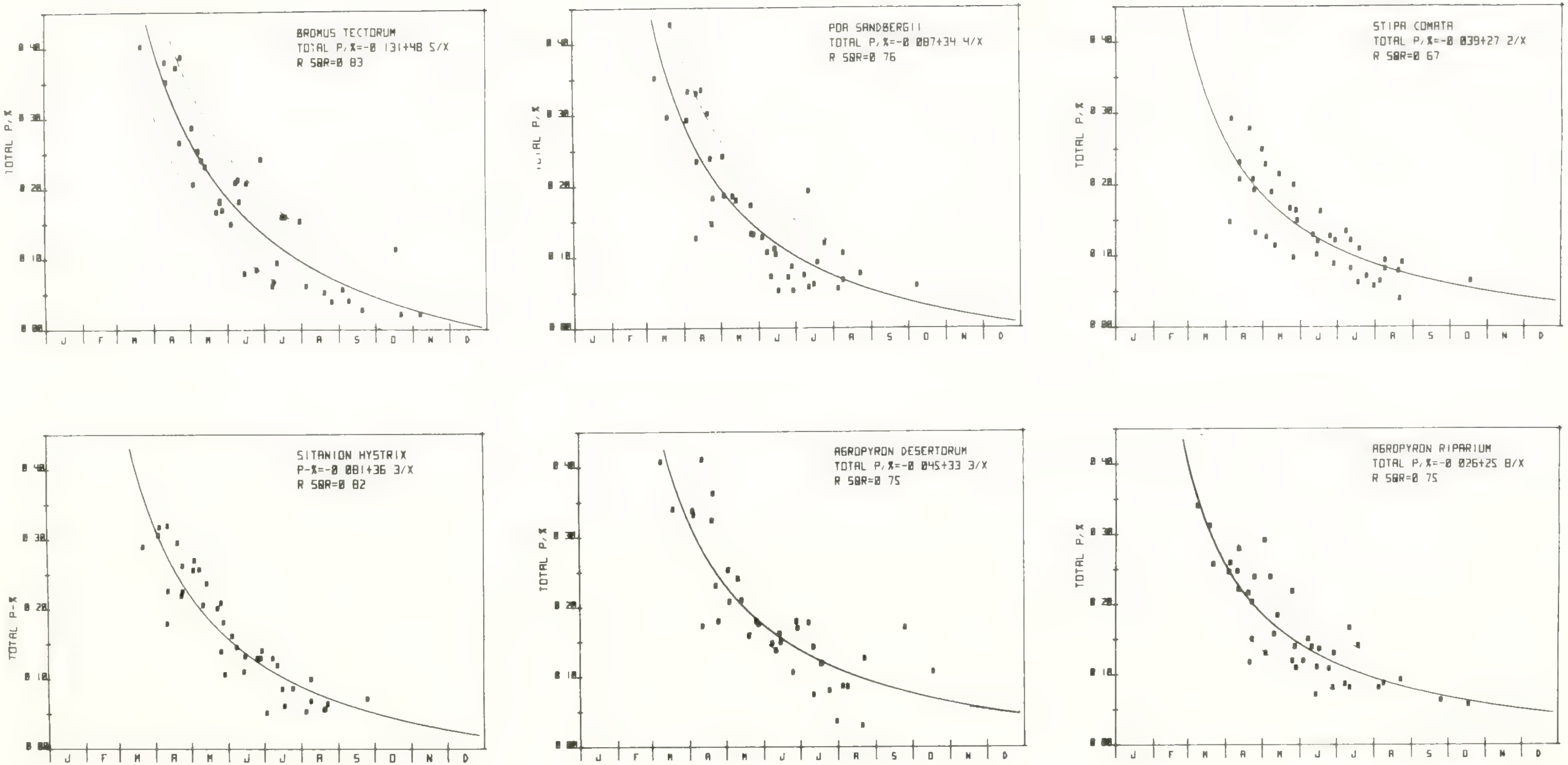
Sulfur and N:S Ratio

The amount of S found in the seven grass species varied from approximately 0.25 to less than 0.05 percent (fig. 12). The level decreased rapidly from April through June. Cheatgrass was particularly low in S after reaching maturity, while needle-and-thread grass, streambank wheatgrass, and desert wheatgrass appeared to maintain levels near the required 0.1 percent S (NAS-NRC 1976).

Allaway (1969) states that the S requirement for ruminant animals is best expressed in terms of the N:S ratio of forage, and that the optimum should be 10:1 to 15:1. These ratios for the seven grass species are shown in figure 13.

The N:S ratios exhibited considerable scatter in cheatgrass, bluegrass, and wildrye. With the exception of bluegrass, there was a definite narrowing trend in the ratio as the season progressed. The individual N and S curves show that N levels continued to decrease while S levels tended to level; this has the effect of narrowing the ratio.

We assume that when the ratio is wider or narrower than given by Allaway (1969) the animal may have a reduced protein conversion efficiency and may also suffer nutritional problems. The data indicate that for some species (desert wheatgrass, needle-and-thread grass, and bottlebrush squirreltail) the N:S ratios are narrower than presumed adequate before the end of the grazing season. However, the bulk of the forage on the experimental range is cheatgrass, which has ratios within the desired range throughout the grazing season. Therefore, we conclude that on cheatgrass ranges, nutritional problems associated with N:S ratios are not serious, but the low levels of N and S by themselves are the biggest problem.



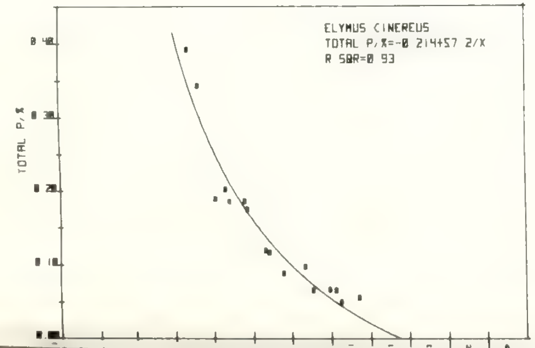
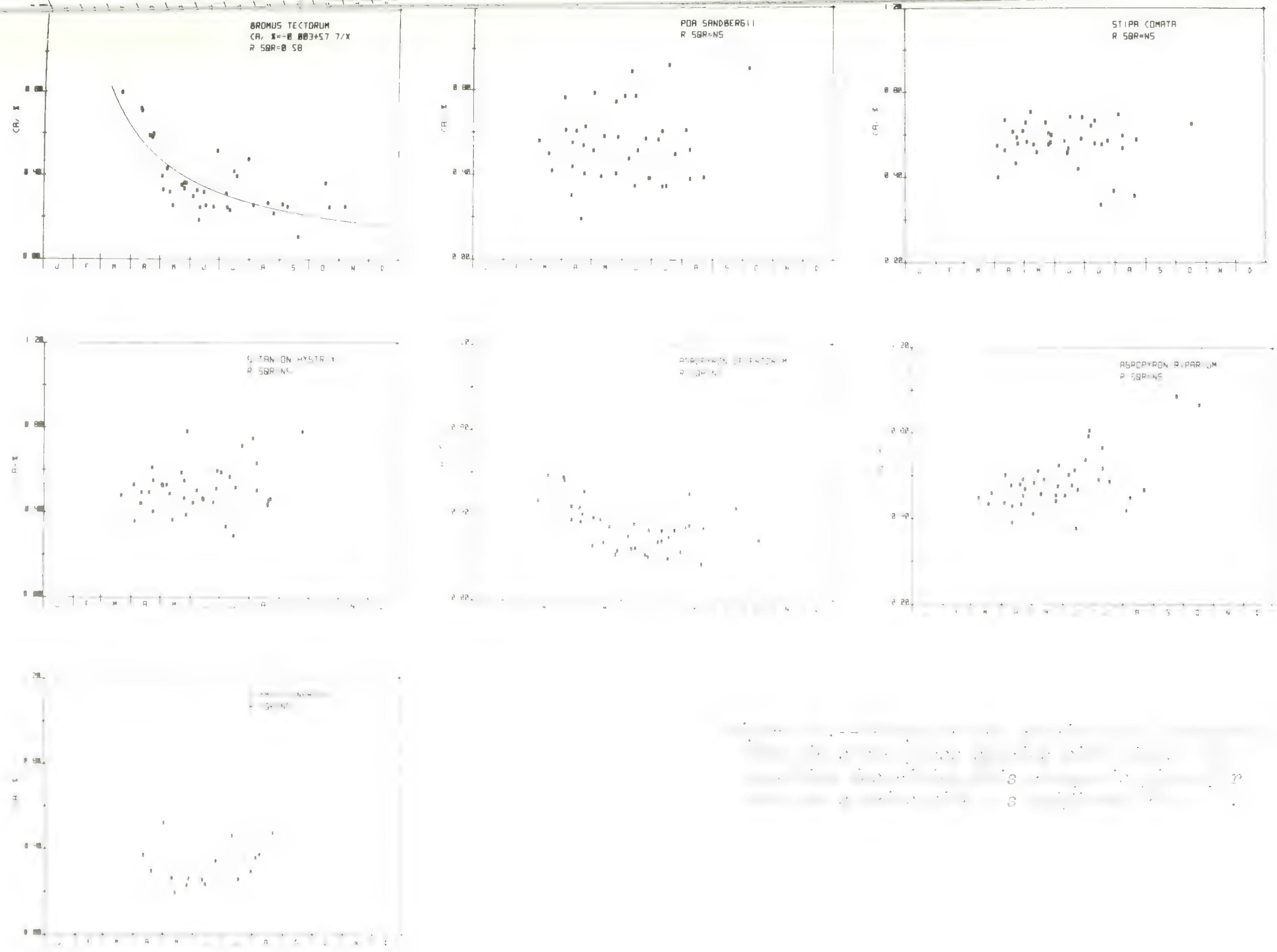


Figure 9.--Change in the total phosphorus (P) concentration in seven grass species with time. The equations describing this change and r^2 values are given for each species.


BROMUS TECTORUM
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R SQR=0.58
CA, %
0.80
0.40
0.00
J F M A M J J A S O N D
POA SANDBERGII
R SQR=NS
CA, %
0.80
0.40
0.00
STIPA COMATA
R SQR=NS
CA, %
1.20
0.80
0.40
0.00
SITANION HYSTRIX
R SQR=NS
1.20
0.80
0.40
0.00
AGROPYRON R SQR=NS
1.20
0.80
0.40
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AGROPYRON RIPARIUM
R SQR=NS
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0.80
0.40
0.00

[illegible]

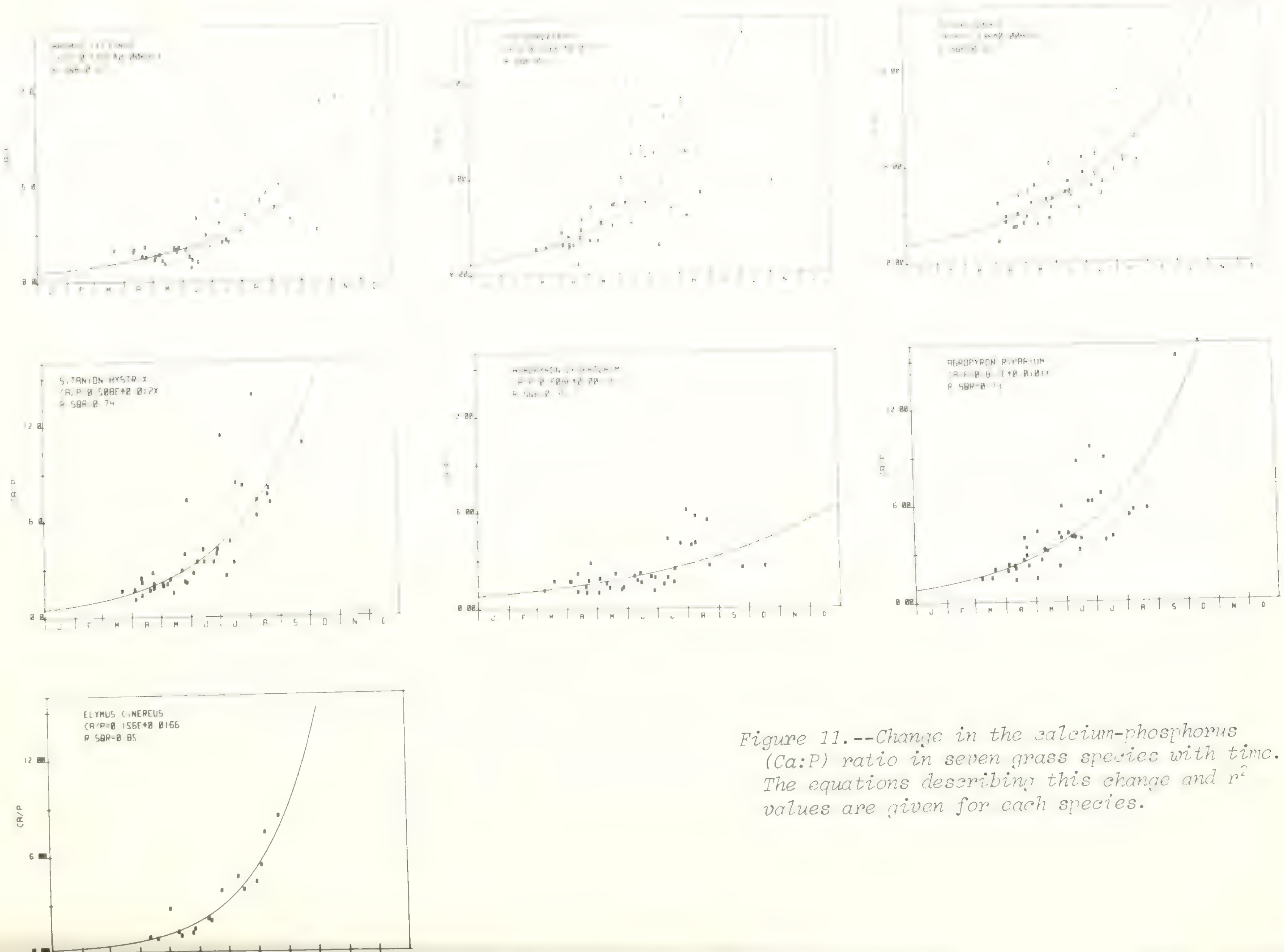
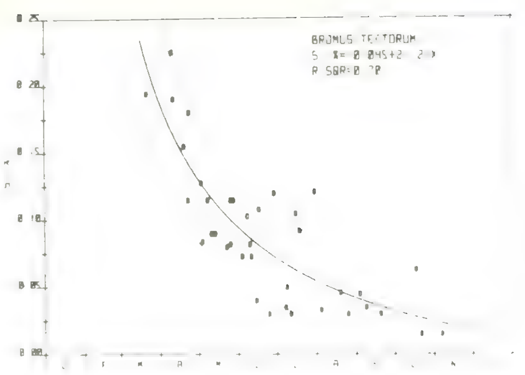


Figure 11.--Change in the calcium-phosphorus (Ca:P) ratio in seven grass species with time. The equations describing this change and r^2 values are given for each species.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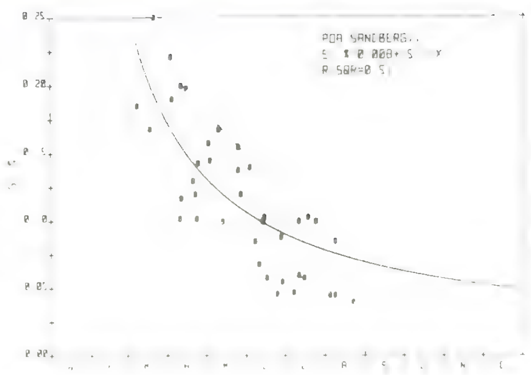
0 10
0 05
0 00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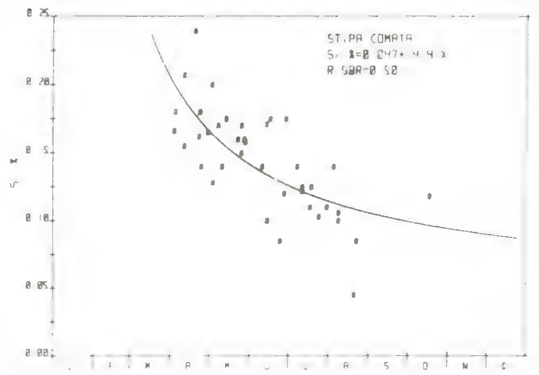
0 15
0 10
0 05
0 00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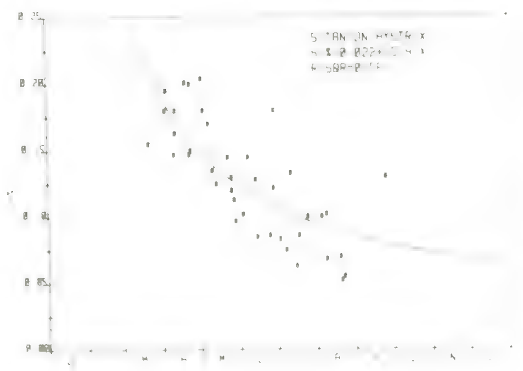
0 10
0 05
0 00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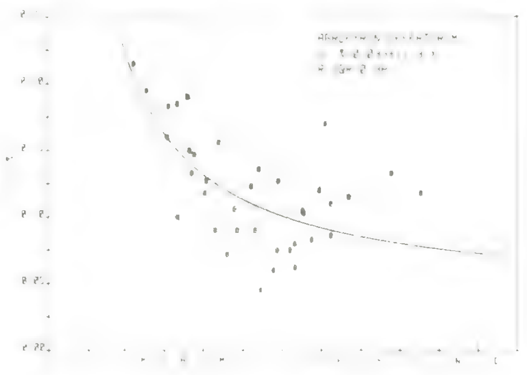
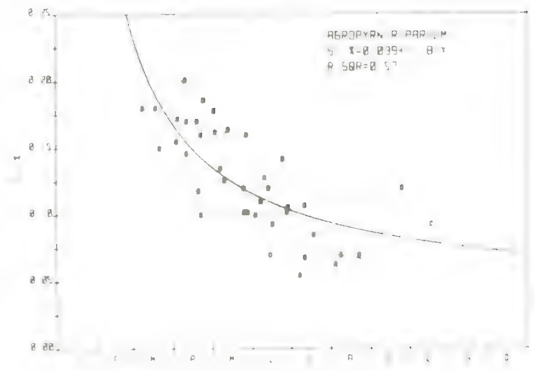
0 15
0 05

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R SQR=0 57
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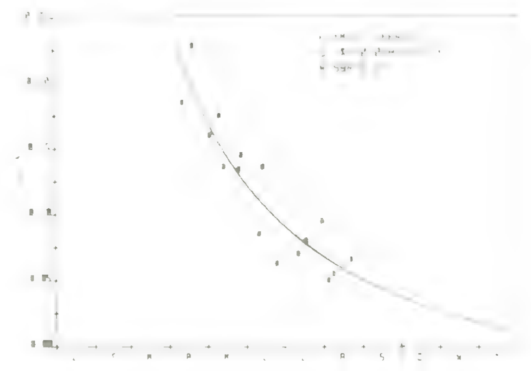
0 20
0 15
0 05
0 00



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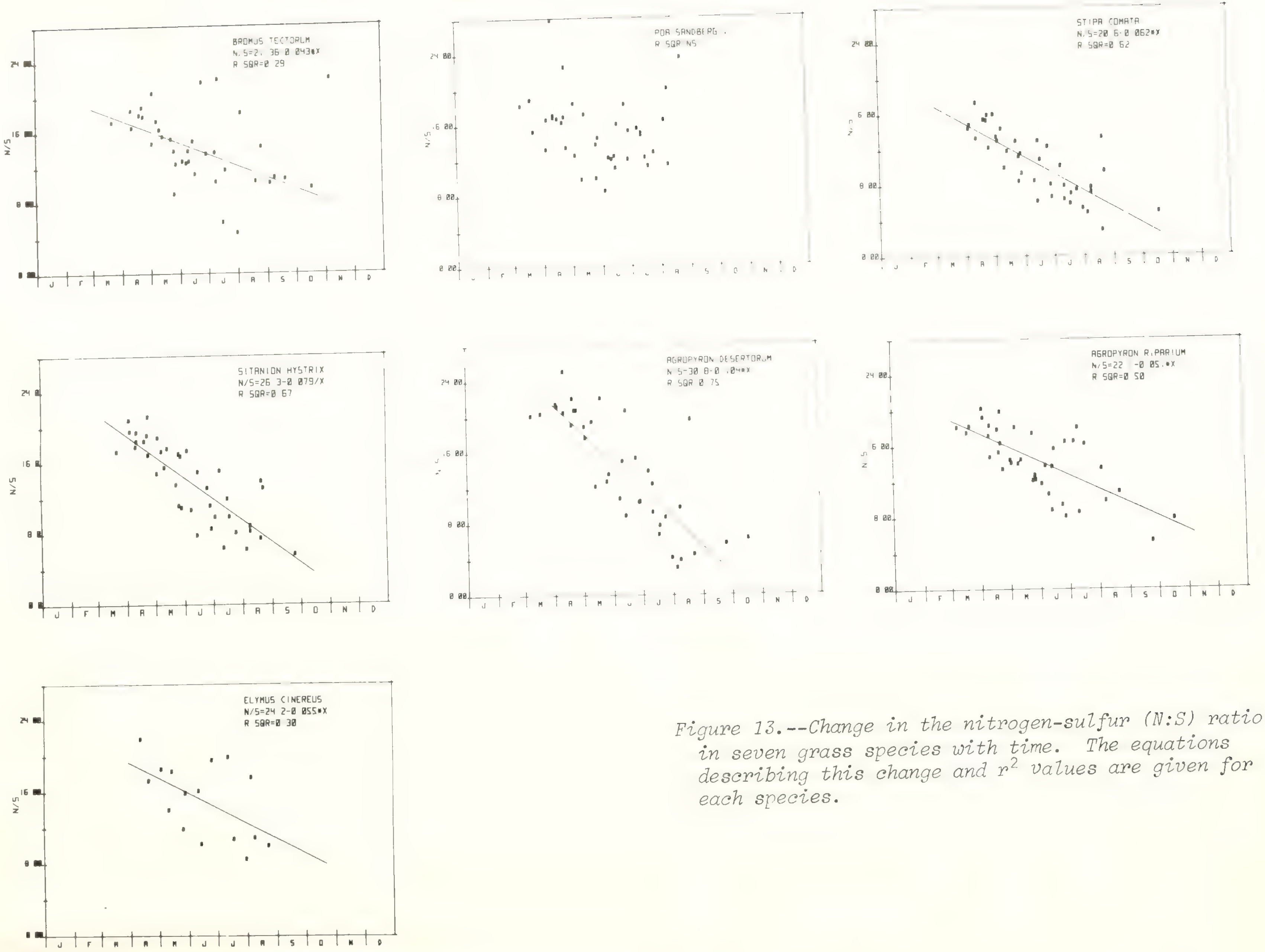


Figure 13.--Change in the nitrogen-sulfur (N:S) ratio in seven grass species with time. The equations describing this change and r^2 values are given for each species.

Potassium

The K concentrations (fig. 14) in the early spring varied considerably between species. Basin wildrye had values in excess of 4 percent K, while needle-and-thread grass had less than 2 percent K. The decrease in the K level is rapid, and by late July most species had values less than 1 percent K.

Lawton and Cook (1954), in their review of the role of potassium in plant nutrition, indicate that most common grasses contain between 0.8 and 1.5 percent K. Our values exceed this range during the early part of the season, decline to levels within the range, and later in some species fall to much lower levels. The high K values encountered in early spring undoubtedly contribute to the occurrence of grass tetany, especially in lactating cows, following turnout to spring range (Grunes and others 1970). Cattle, however, have not experienced tetany problems at Saylor Creek.

NAS-NRC (1976) states that the potassium requirements for beef cattle have not been critically measured, but indicates the optimum level for growing and finishing steers is between 0.6 and 0.8 percent K of the ration.

Our data strongly suggest that while some of these range grasses contain excessive K in early spring, K deficiencies could occur after July.

Magnesium

The Mg concentrations (fig. 15), like Ca, were extremely erratic. Only cheatgrass showed a decline in magnesium levels with advances in season. The majority of the forage samples had concentrations between 0.1 and 0.2 percent Mg.

Magnesium requirements of lactating beef cows have been determined as approximately 0.18 percent of dry matter (NAS-NRC 1976).

Allaway (1969) reported that in many cases of grass tetany, feeds have contained less than 0.2 percent Mg; the ratio K:(Ca + Mg), on an equivalence basis, has been wide; and concentrations of citric, aconitic, or both acids have been greater than 1 percent in the plants. Kemp and 't Hart (1957) explain that when the ratio is less than 2.2:1 there are few incidences of grass tetany. They indicate the cool weather in the spring decreases plant uptake of K, while the uptake of Ca and Mg remains constant, thus causing the ratio to narrow.

The K:(Ca + Mg) ratio, calculated on an equivalent basis, is shown in figure 16. Basin wildrye and desert wheatgrass are the two species that have ratios greater than 2.2:1. Wildrye exceeded the 2.2:1 value for much of the spring period, but the amount of this species on the range is small and thus should not present any nutritional problems. The general trend is a narrowing of the ratio with advance in season.

Sodium

No relation was found between Na concentration and date for any of the seven grass species (fig. 17).

Animal requirements are reported to be about 500 ppm Na (NAS-NRC 1976) which is greater than the levels found in these forages. Sodium chloride (NaCl), however, is generally provided for animals as a part of normal management operations.

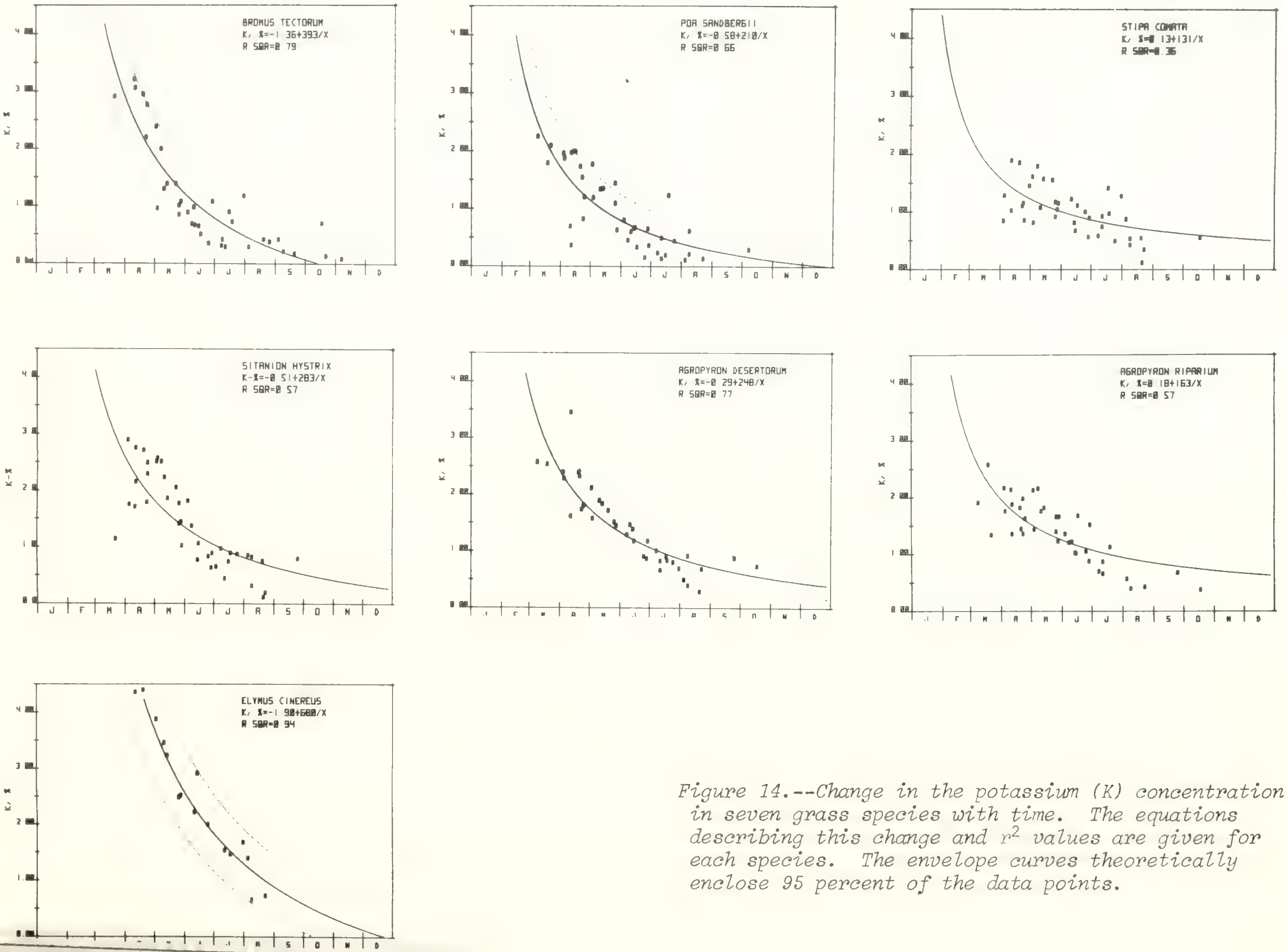


Figure 14.--Change in the potassium (K) concentration in seven grass species with time. The equations describing this change and r^2 values are given for each species. The envelope curves theoretically enclose 95 percent of the data points.

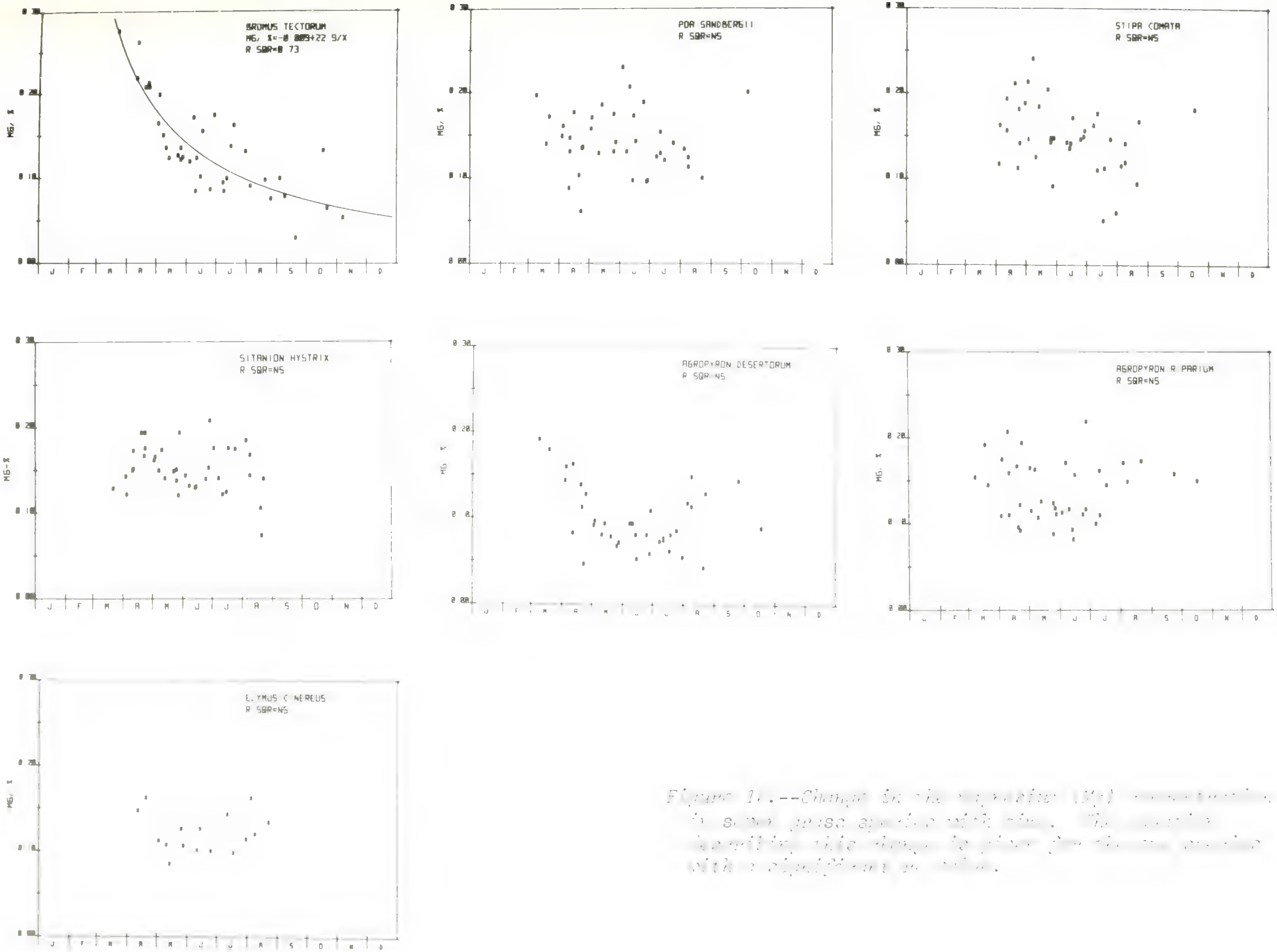


Figure 1[illegible].--Change in the magnesium (Mg) concentration in seven grass species with time. The equation describing this change is given for Bromus tectorum with a significant r² value.

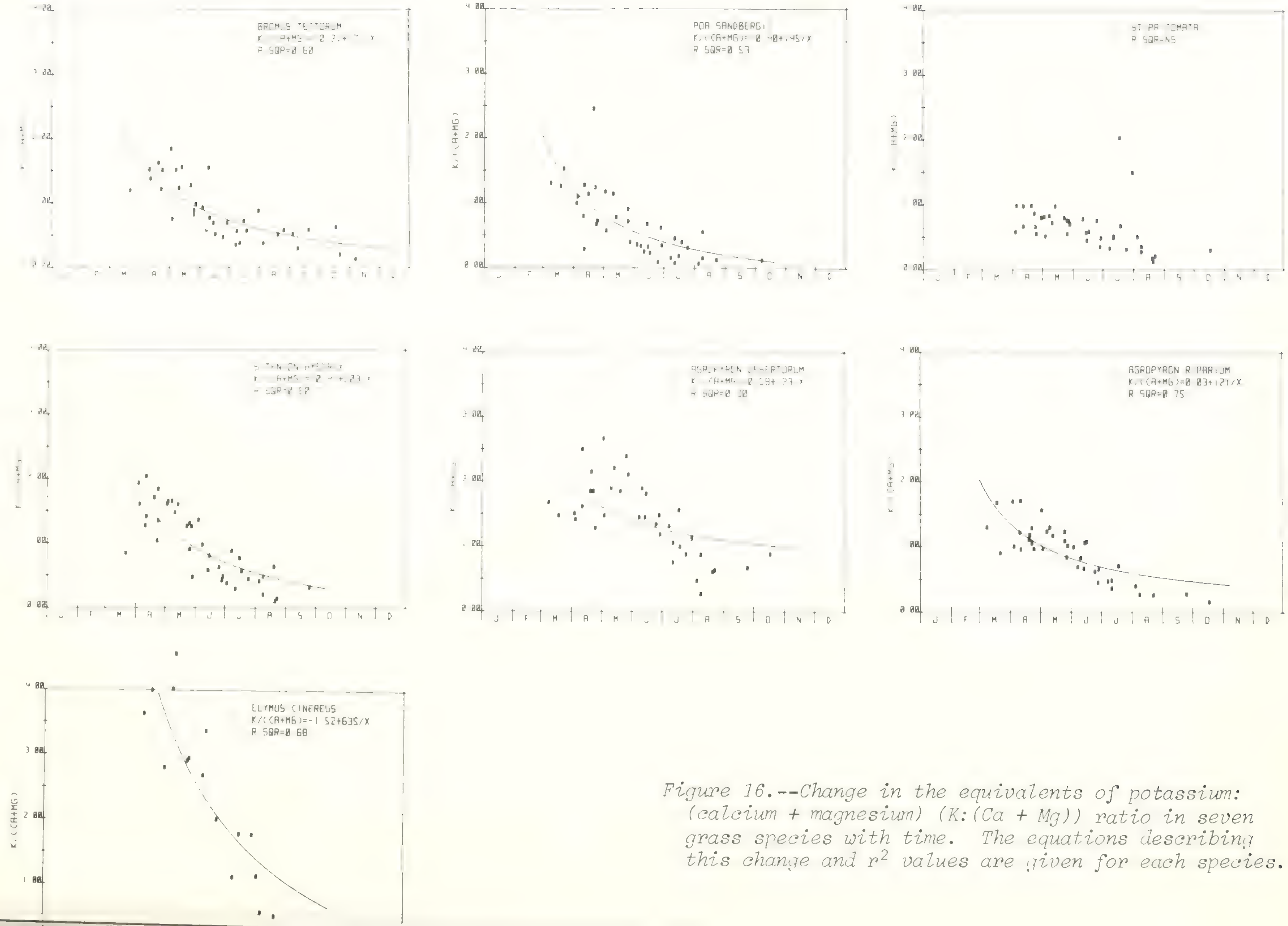
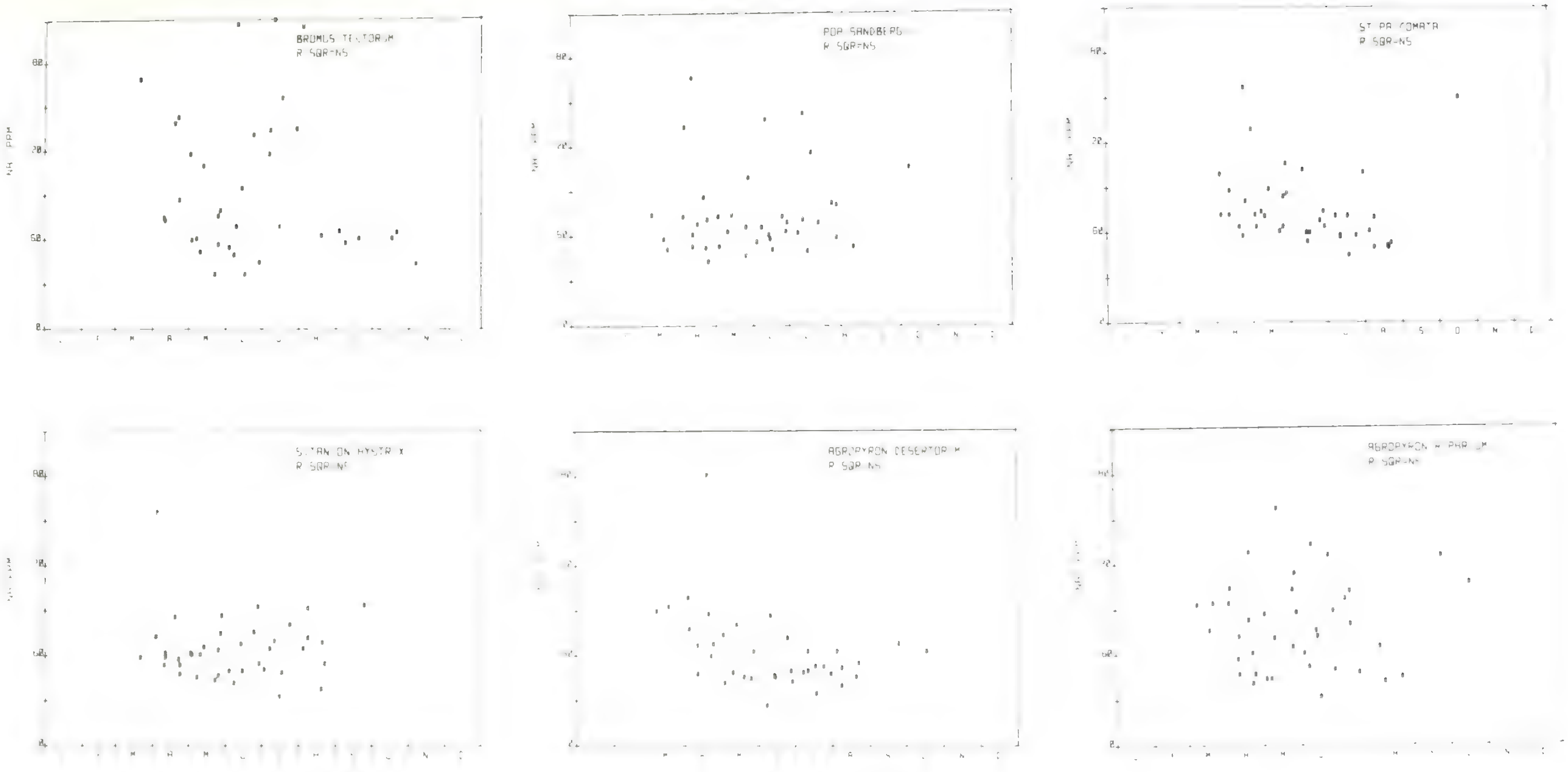
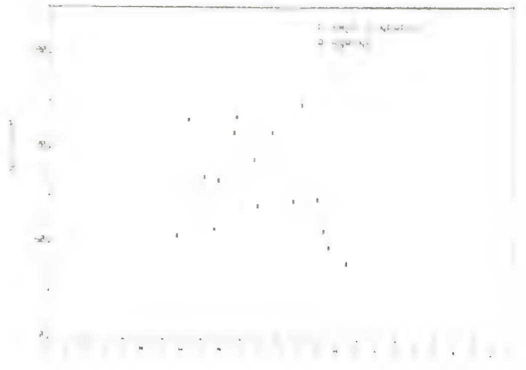


Figure 16.--Change in the equivalents of potassium: (calcium + magnesium) (K:(Ca + Mg)) ratio in seven grass species with time. The equations describing this change and r^2 values are given for each species.


BROMUS TECTORUM
R SQR=NS
POA SANDBERG
R SQR=NS
STIPA COMATA
R SQR=NS
SITANION HYSTRIX
R SQR=NS
AGROPYRON DESERTORUM
R SQR=NS
AGROPYRON X PHR
R SQR=NS
80
20
60
0
NH PPM
J F M A M J J A S O N D


R SQR=NS

[illegible]

Zinc

Decreasing trends in forage Zn concentration (fig. 18) are noted as the forage matures and concentrations are in the 20 to 30 ppm Zn (NRC-recommended levels) range for a brief period in early spring.

Mayland (1975) noted the trends of Zn, as reported here, were declining below adequate levels as forage matured; supplemental zinc was fed to cows and calves. Bot the cows and calves showed increased weight gains due to the added zinc.

The Zn:Ca and Zn:Cu values are shown in figures 19 and 20, respectively. These ratios are of interest because these ions may compete for absorption sites in the ani There do not appear to be any significant trends with date.

Manganese

Manganese concentrations (fig. 21) varied widely between species and dates. Bas wildrye contained the lowest Mn concentrations of the seven species analyzed.

Beef cattle requirements range from 1 to 10 ppm Mn in the forage (NAS-NRC 1976). The levels reported here are far in excess of the requirement, and thus Mn should not be deficient in cattle diets on cheatgrass range.

Copper

Copper levels (figure 22) exhibited downward trends with increased forage maturi in five of the seven species. Copper content in cheatgrass and streambank wheatgrass was not correlated with maturity.

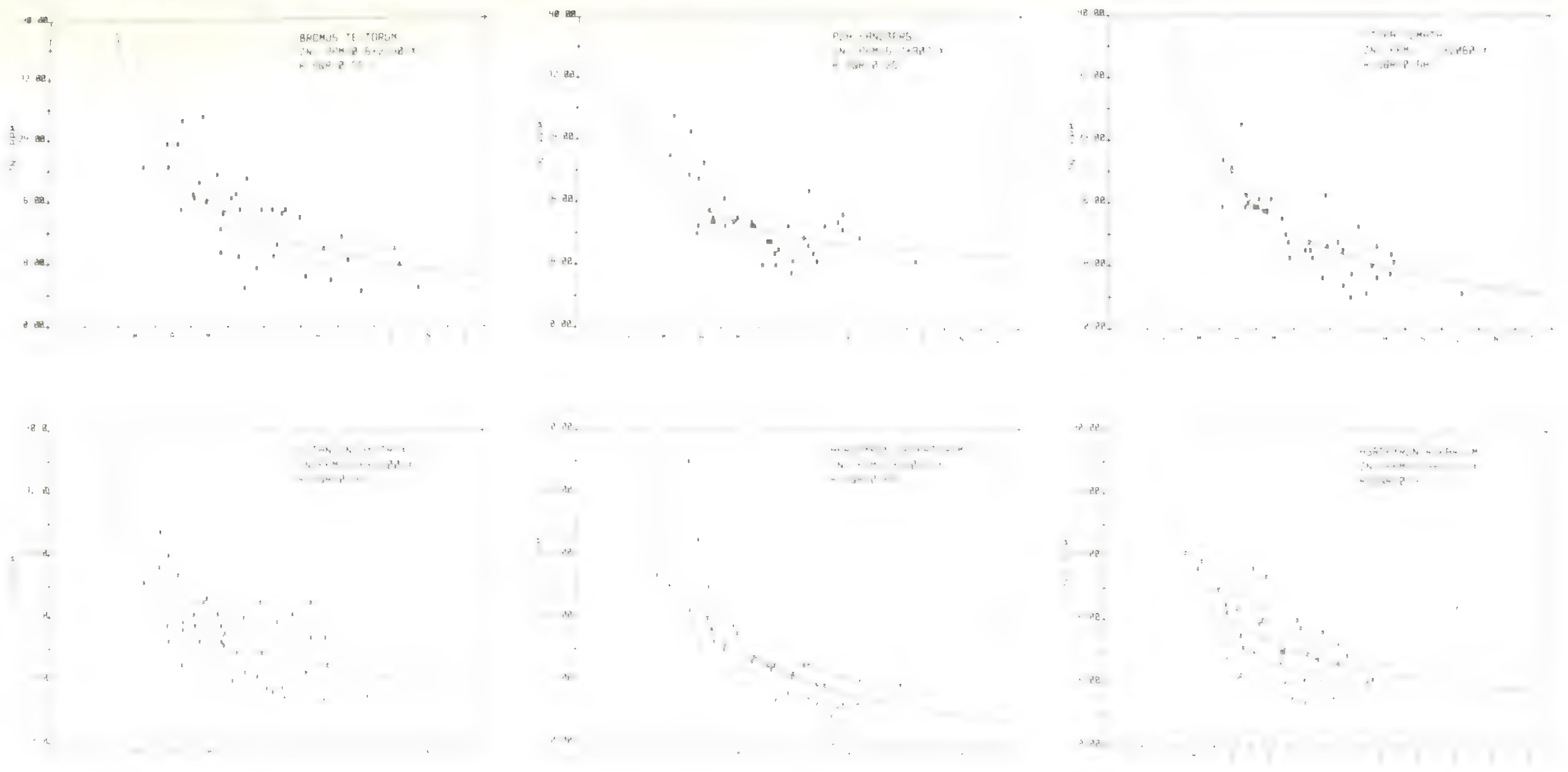
NAS-NRC (1976) lists the Cu requirement for beef cattle at 4 ppm Cu in the ratio dry matter. Only a few samples contained less than 4 ppm Cu, therefore Cu should not be deficient in the diet of animals grazing cheatgrass ranges. If molybdenum (Mo) va ues are high (>6 ppm), then dietary Cu values should be increased 2 to 3 times because of the depression in Cu absorption by Mo. The Mo values of a few random forage sampl from this area indicated <3 ppm Mo. Therefore, Cu values in the forage grown on this range are considered adequate for beef cattle.

Iron

The concentrations of Fe (figure 23) in forage samples from Saylor Creek far exceeded the levels normally expected in plant tissue grown in dust-free environments However, values of this magnitude are often encountered in range plants. The large values are attributed, in part, to soil contamination, which is verified by plotting the Fe concentration against the percent NDF-ash (insoluble silica and soil contamination). Although there is considerable scatter to the points, it is apparent that significant increases in Fe levels accompany increased NDF-ash. These plots are show in figure 24.

Forage Quality Measures

Forage quality can be defined in many ways, but it usually is related to some animal response, such as feed intake, weight gain, or production of milk or wool (Dietz 1970). Nutritive composition and digestibility also provide measures of forage quality.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40.00
32.00
24.00
16.00
8.00
0.00

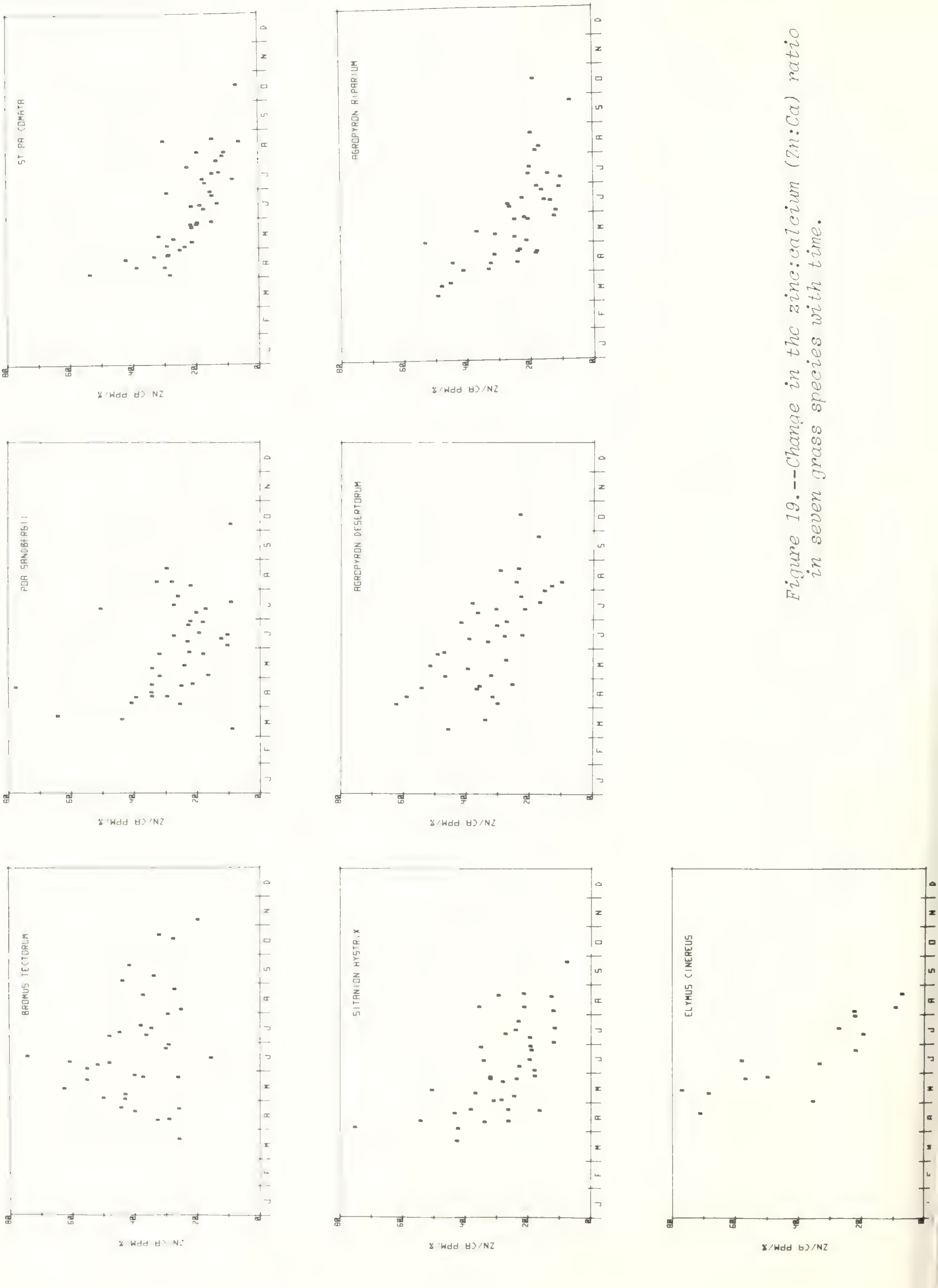
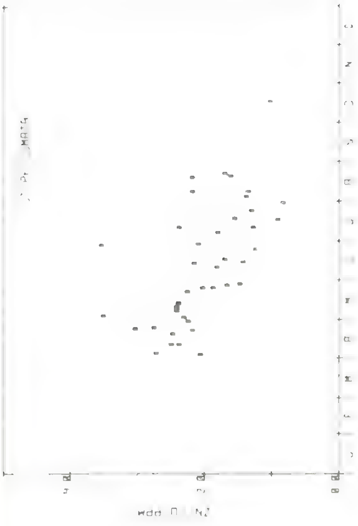


Figure 19.--Change in the zinc:calcium (Zn:Ca) ratio in seven grass species with time.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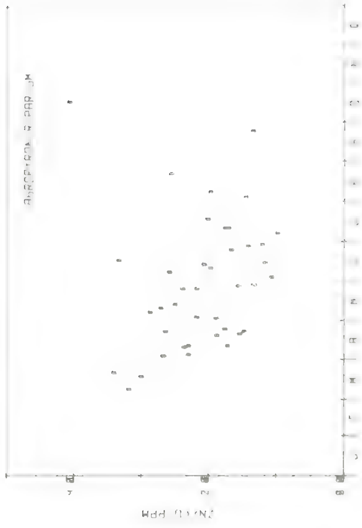
4
2
0
J F M A M J J A S O N D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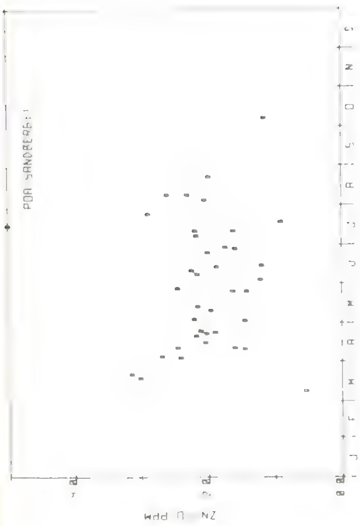
4
2
0
J F M A M J J A S O N D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ZN (1) PPM
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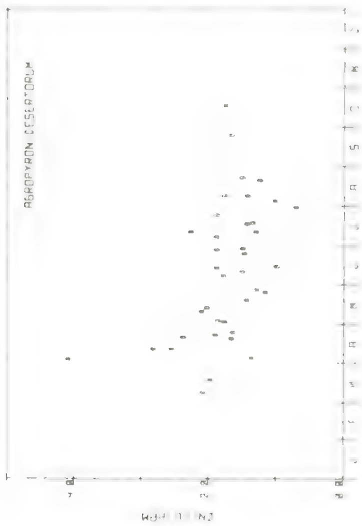
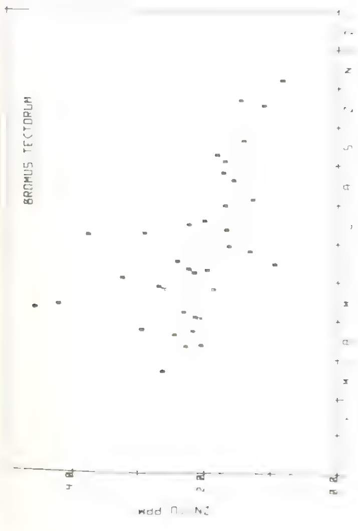
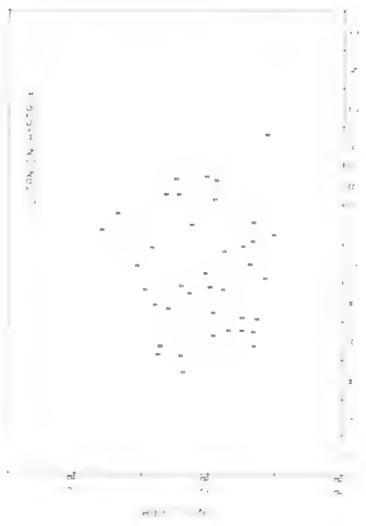
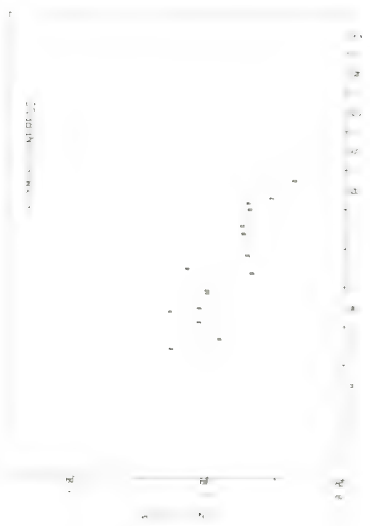
2
0
J F M A M J J A S O N D


AGROPYRON DESERTORUM
ZN (1) PPM
4
2
0
J F M A M J J A S O N D


BROMUS TECTORUM
ZN (1) PPM
4
2
0
J F M A M J J A S O N D





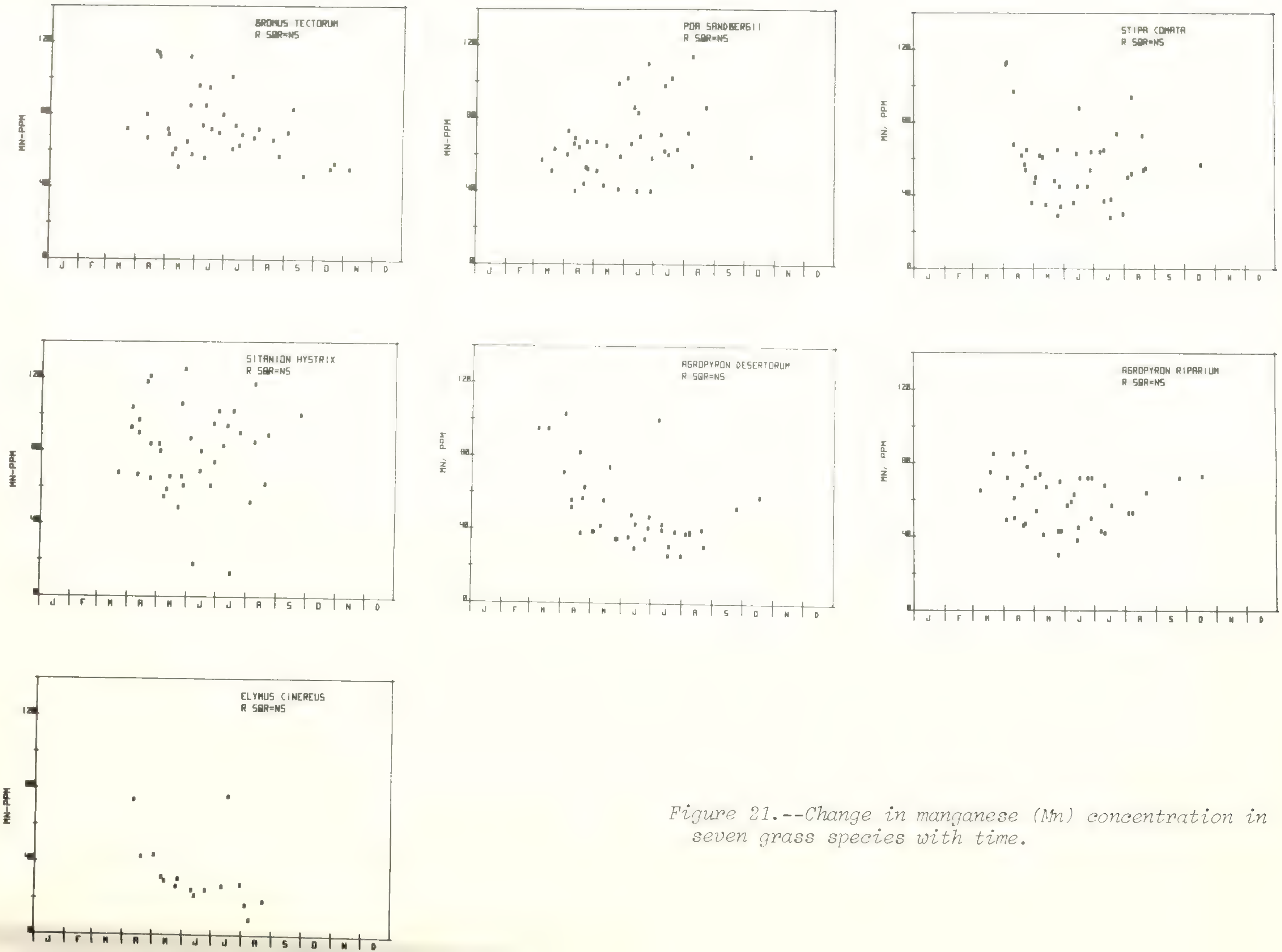
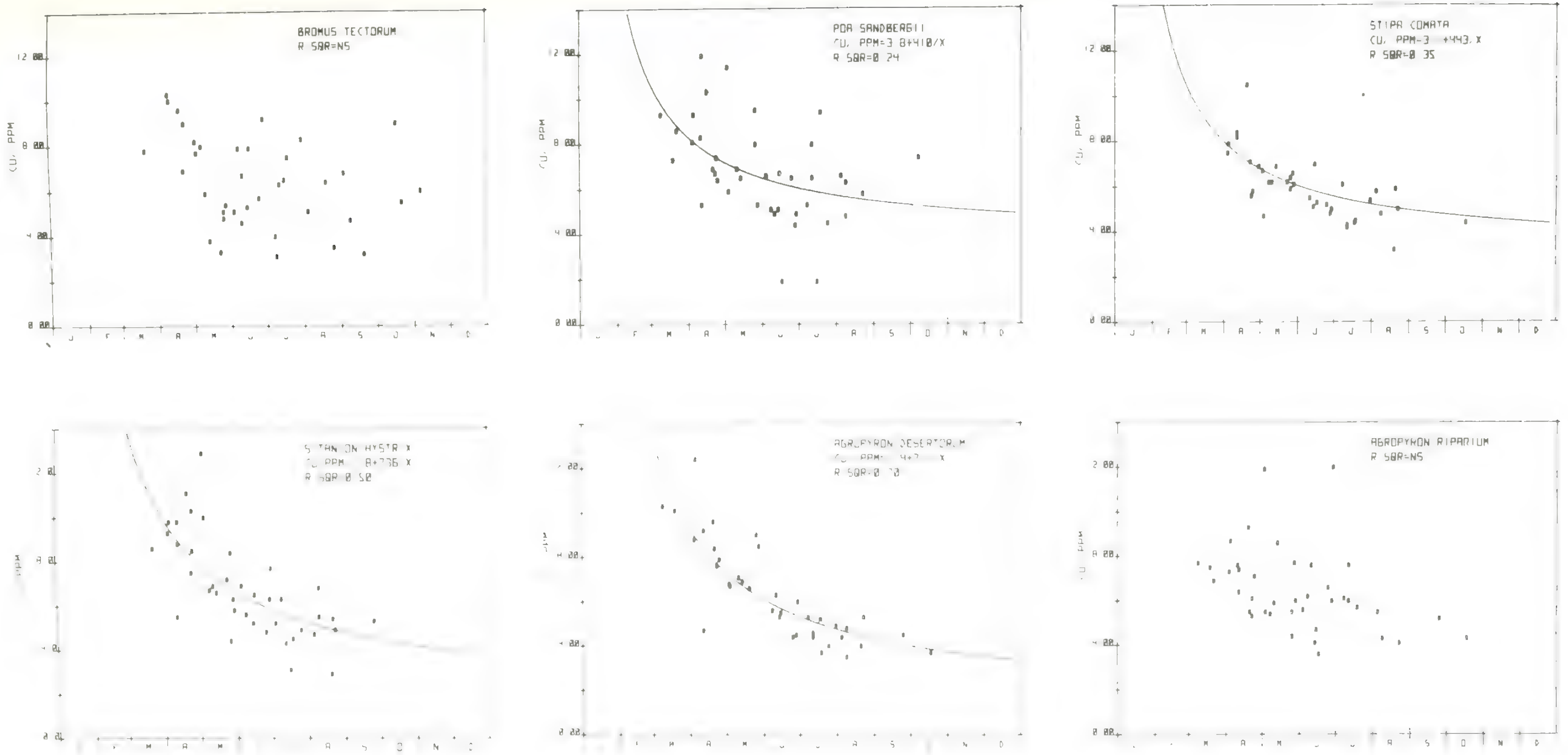


Figure 21.--Change in manganese (Mn) concentration in seven grass species with time.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CU, PPM
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8.00
4.00
0.00
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CU, PPM=3.8+410/X
R SQR=0.24
STIPA COMATA
CU, PPM=3 +443/X
R SQR=0.35
SITANION HYSTRIX
R SQR 0.50
AGROPYRON DESERTORUM
R SQR=0.70
AGROPYRON RIPARIUM
R SQR=NS
2.00
8.00
4.00
0.00

0.00

[illegible]

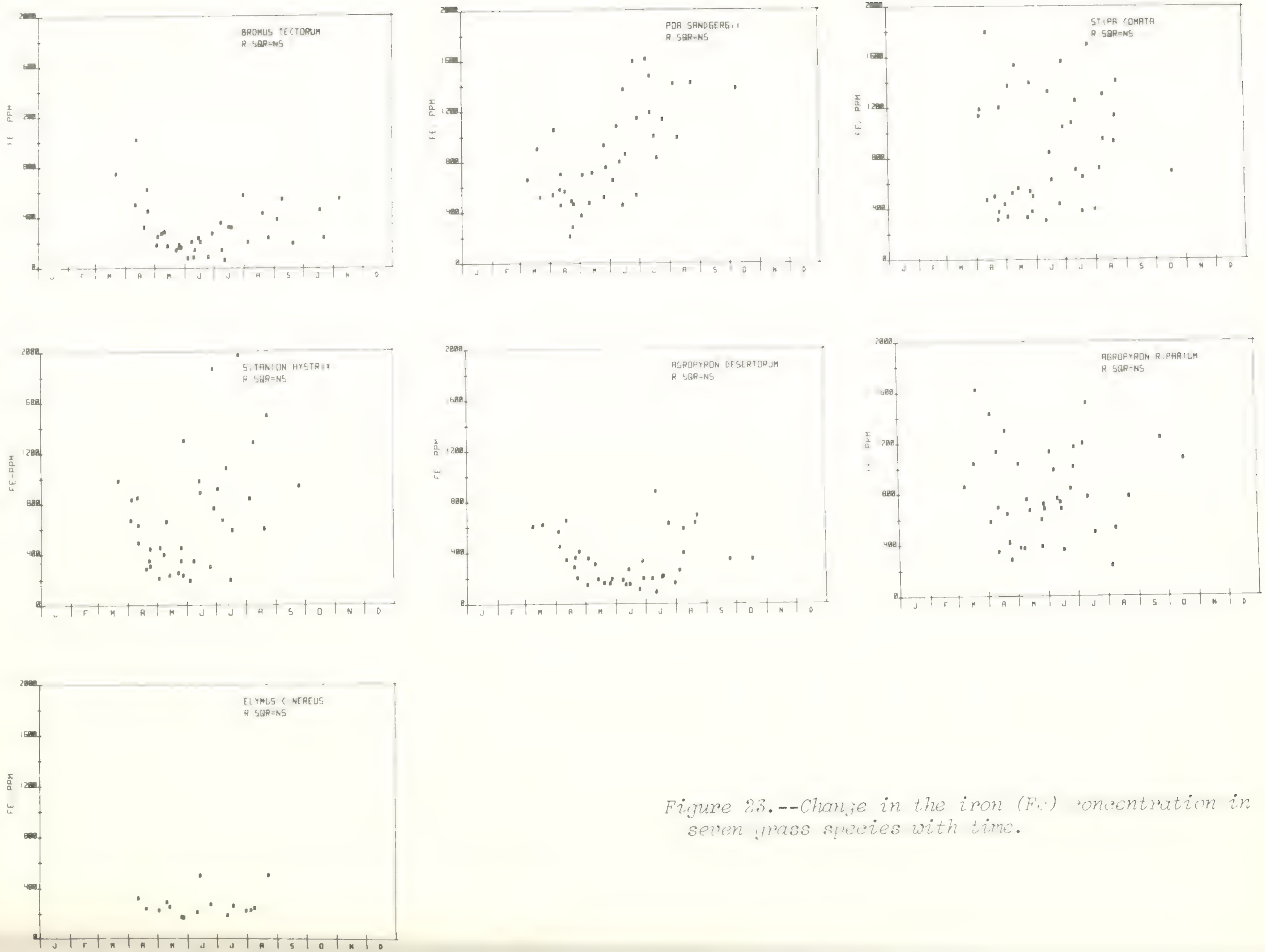
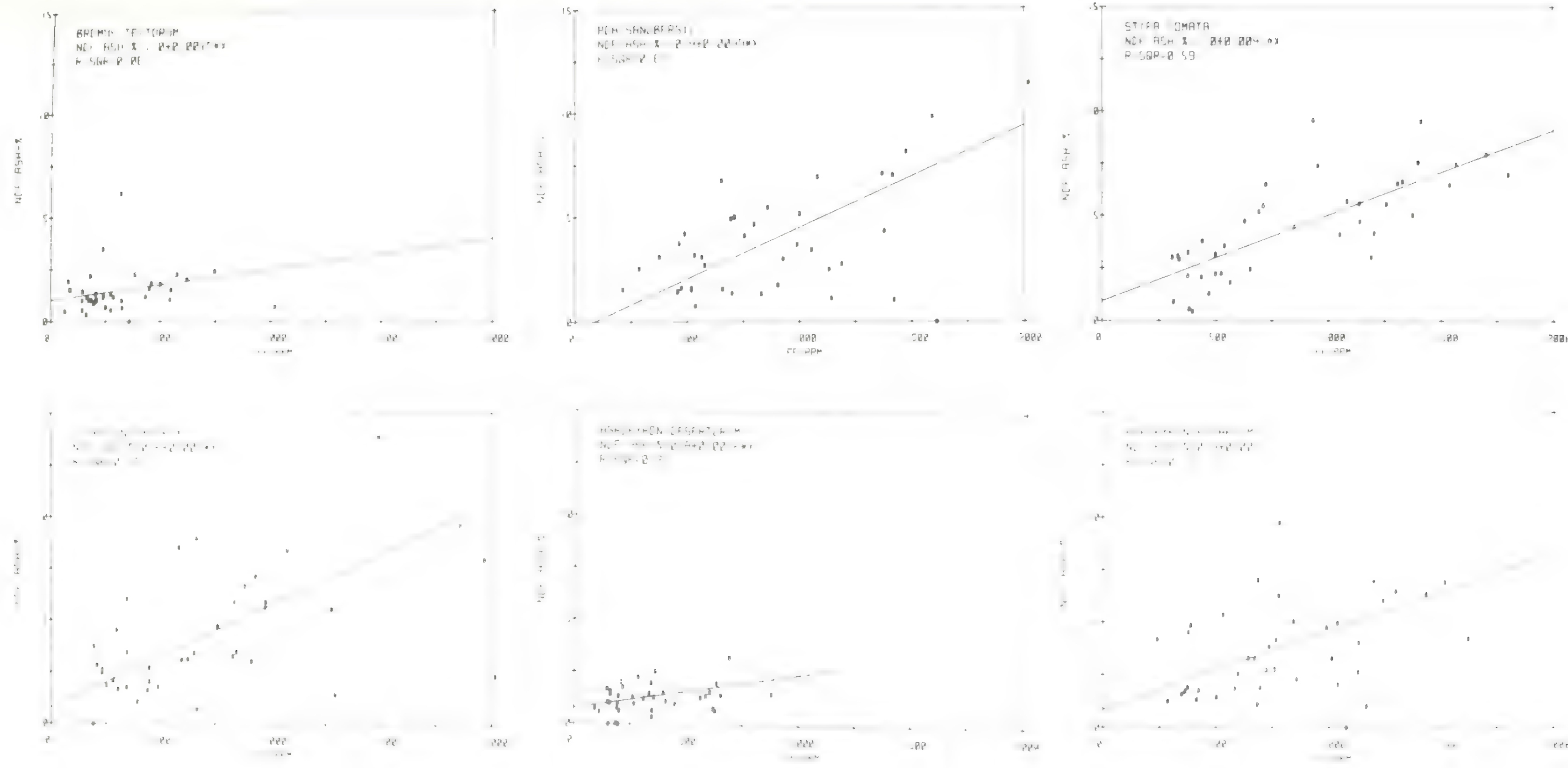


Figure 23.--Change in the iron (Fe) concentration in seven grass species with time.


BROMUS TECTORUM
NDF ASH %
POA SANDBERGII
NDF ASH %
STIPA COMATA
NDF ASH % . 0+0 004 ox
R SQR=0 59
NDF ASH %
PPM
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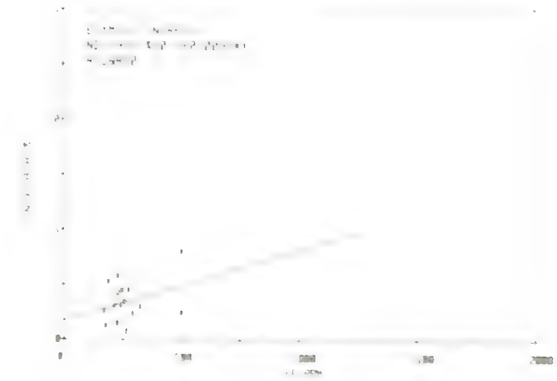
500
1000
1500
2000
5
10
15



[illegible]

A newer method, rapidly gaining favor, determines cell wall residues (total of lignin, cellulose, and hemicellulose) to replace the crude fiber analysis (Van Soest 1966). These residues are considered to be chemical components that cannot be completely digested. The cell wall constituents are separated into components that are: (1) insoluble in a neutral detergent solution (neutral detergent fiber, NDF), (2) soluble in an acid detergent solution (hemicellulose), and (3) insoluble in an acid detergent solution (acid detergent fiber, ADF, which includes cellulose, lignin, lignified nitrogen compounds, and silica). The cell contents are soluble in neutral detergent solution. The method separates the totally digestible from the partially digestible and indigestible components of forage.

The method of Van Soest in Goering and Van Soest (1970) leads to an estimate of the percent digestible dry matter. We present the data for NDF (a measure of the tota fiber), NDF-ash (a measure of plant silica plus any soil contamination present), DCW (cell wall digestibility), DCW-ash free (organic cell wall digestibility, and TDDM (tr dry matter digestibility corrected for ash).

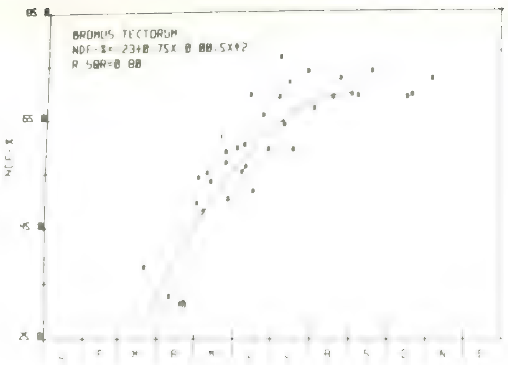
The percent NDF (figure 25) in all species increases with plant maturity. The ra of increase between species is quite similar, but the initial and final percentages va Basin wildrye and needle-and-thread grass had the highest percentage of NDF in the ear spring, and cheatgrass appeared to have the highest percentage at maturity.

The percent NDF-ash (figure 26) did not show any relationship with sampling date. The scatter of values indicates that some species--bluegrass, needle-and-thread grass, squirreltail, and streambank wheatgrass-accumulate more silica, collect more soil dust or both, than the others. Soil contamination is important because animals may ingest considerable minerals. Mayland and others (1975) reported on the amount of soil ingested by cattle at the Saylor Creek Experimental Range. They found that from 0.1 to 1.5 kg, with a median of 0.5 kg, soil was ingested per animal-day on this cheatgrass range.

Cell wall content (fig. 27 and 28) decreased with increased maturity, while NDF increased in the forage. Cheatgrass digestibility (cell wall content) values were erratic and no trends with plant maturity can be shown, even though the NDF percentage was correlated with plant maturity. The rate of decrease in cell wall digestibility was greatest in basin wildrye, followed by desert wheatgrass, streambank wheatgrass, squirreltail, needle-and-thread grass, and bluegrass. The implications are that these species become increasingly indigestible with increasing maturity. By September, all species except cheatgrass and bluegrass were less than 50 percent digestible.

The estimated true dry matter digestibility (fig. 29) is a measure of the digestible cell contents and digestible lignified cell wall corrected for silica content. Th NDF percentage subtracted from 100 gives the cellular content. The digestible cell wa percentage (100-NDF percentage) minus the silica correction gives the TDDM. Expected apparent dry matter digestibilities or total digestible nutrients (TDN) are about 13 units lower than TDDM due to the loss of metabolic matter in the feces.

The graphs show that the TDDM is greater than DCW. The TDDM follows patterns similar to DCW, and the rates of decrease are similar. Again, by September most speci were less than 60 percent digestible. In another study, dry matter digestibilities of 72, 63, and 65 were determined for mid-July, mid-August, and early September, respectively, using esophageal fistulated yearling cattle and lignin and chromic oxide techniques (Olsen 1971). The higher digestion coefficient for mid-July may be attributed to considerable quantities of green Russian thistle being grazed during this period. The green thistle is readily eaten and is quite nutritious (table 9). The in vivo data also reflect animal preferences for forage species and plant parts, while our data are for total top growth.


BROMUS TECTORUM
NDF-%= 23+0 75X 0 00.5X↑2
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45
25
NDF-%
F
M
A
M
A
S
O
N
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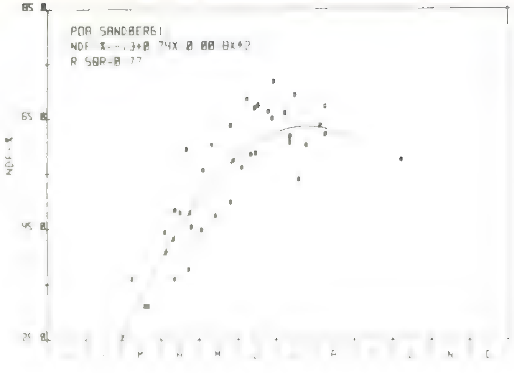
POA SANDBERGI
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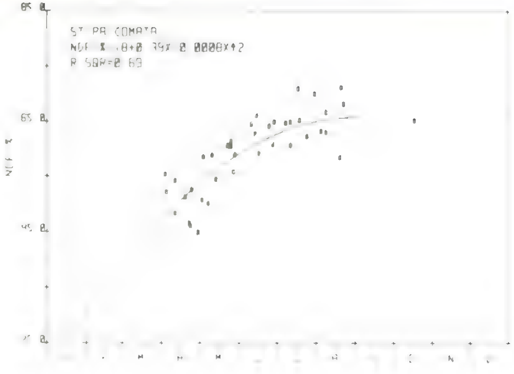
R SQR-0 77
85
65
45
25
NDF-%
M
M
A
N
D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65
45
NDF-%
M
M
M
A
N

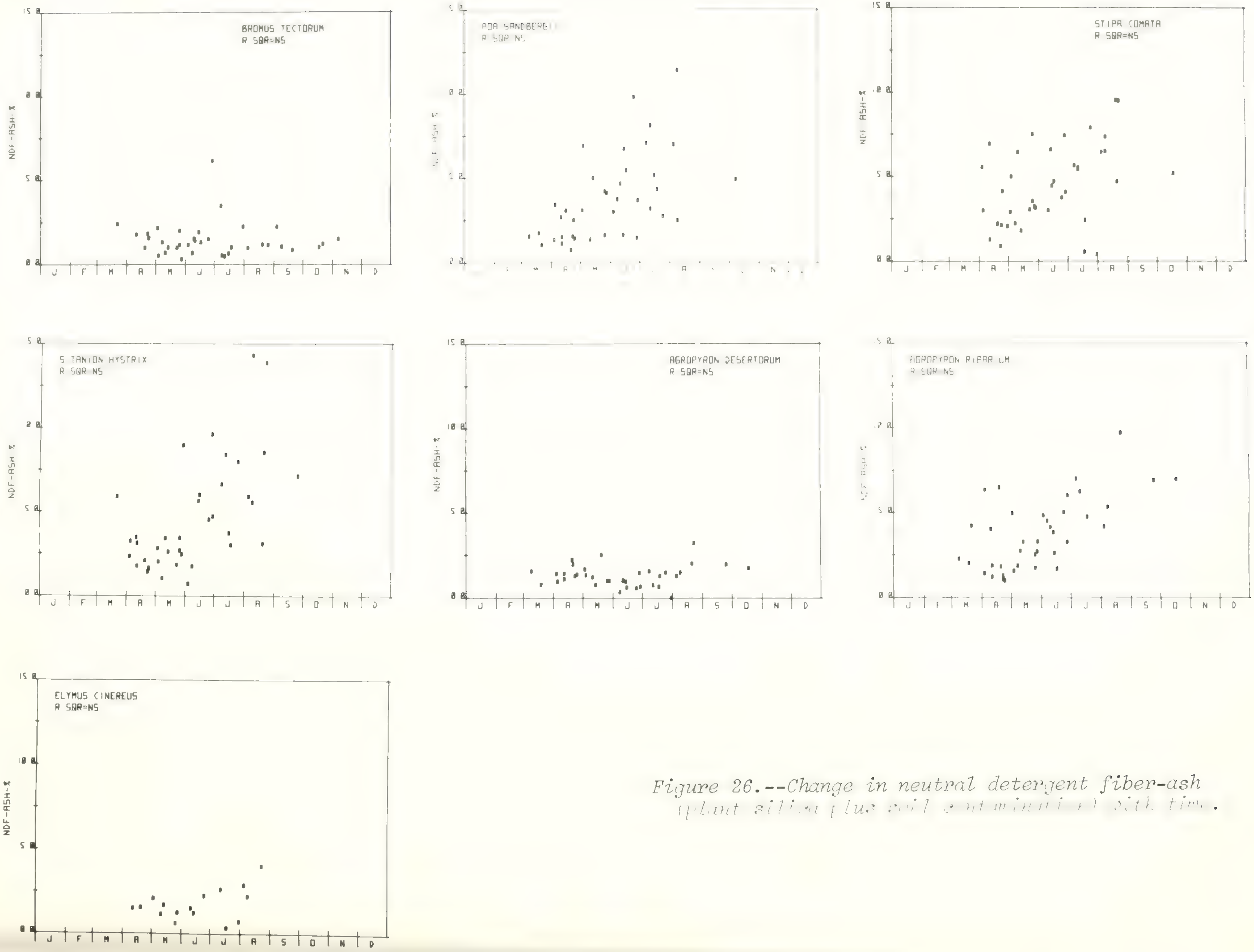
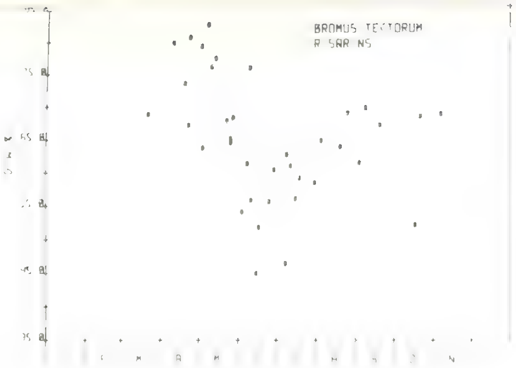
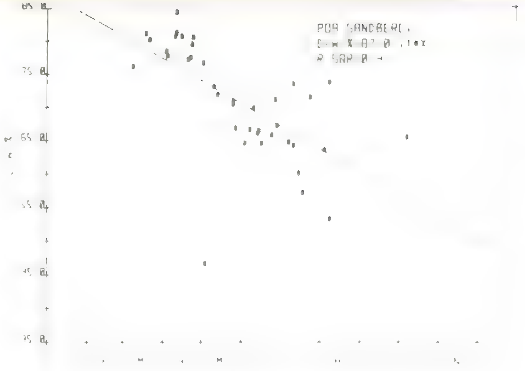
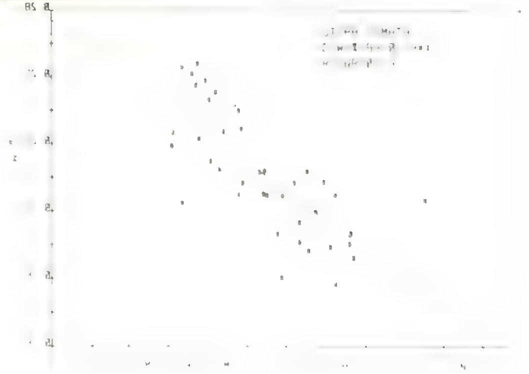
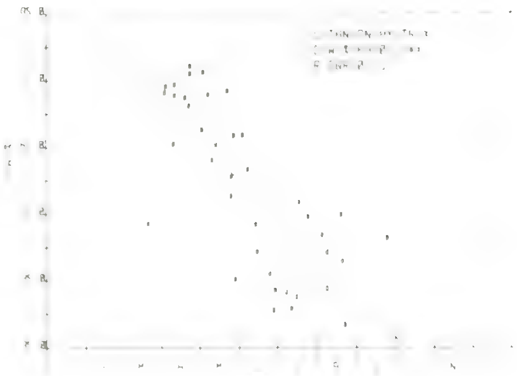


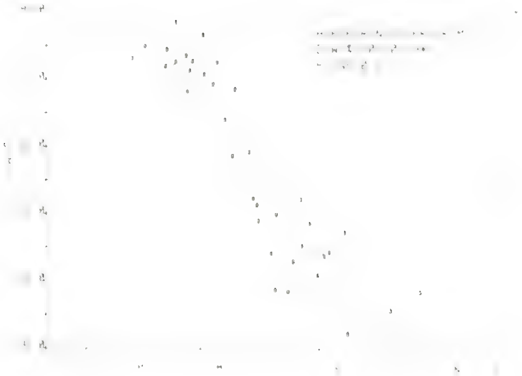
Figure 26.--Change in neutral detergent fiber-ash (plant silica plus soil contamination) with time.

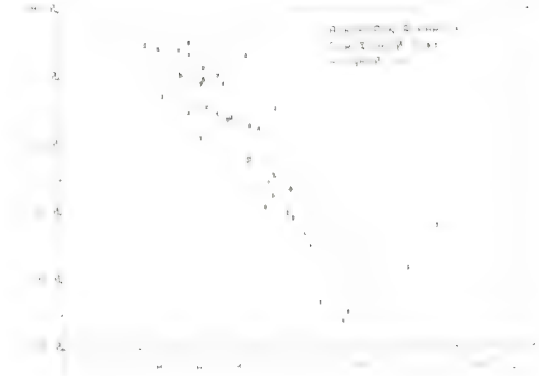

BROMUS TECTORUM
R SAR NS


POA SANDBERGI
R SAR









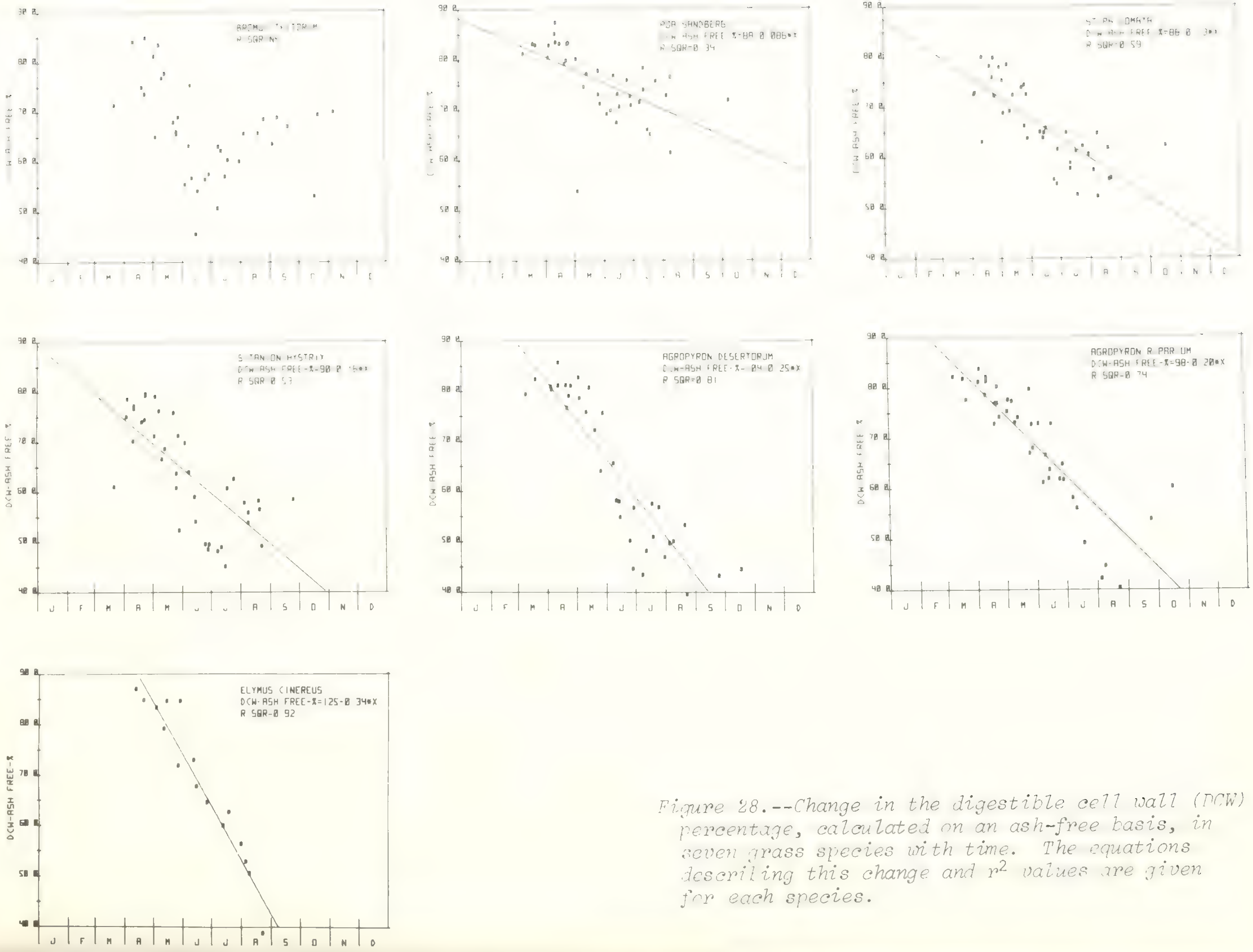
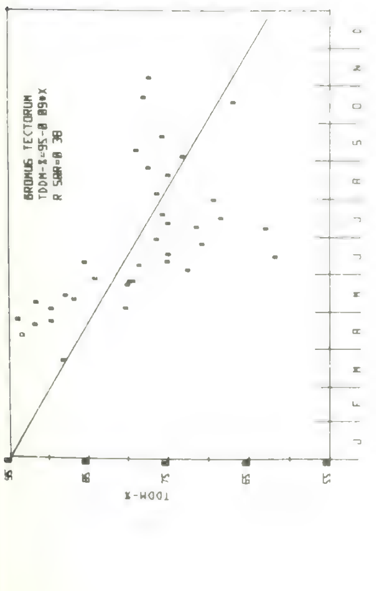
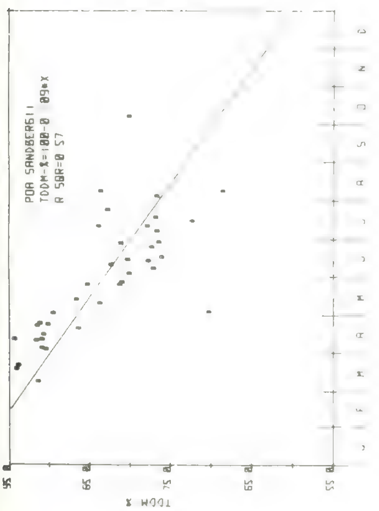
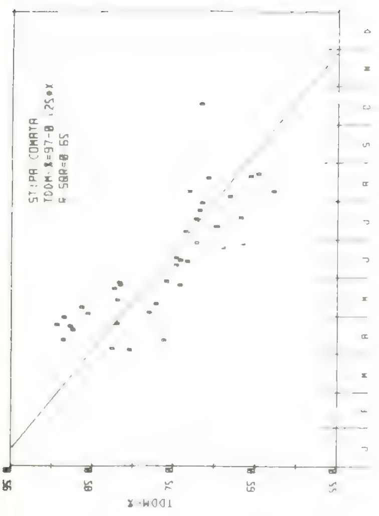
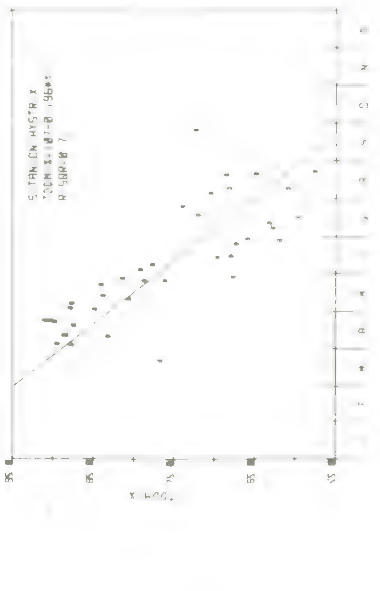


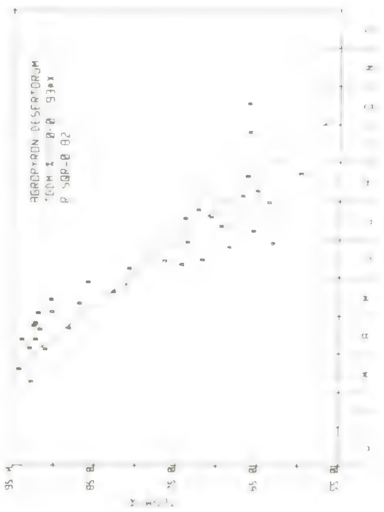
Figure 28.--Change in the digestible cell wall (DCW) percentage, calculated on an ash-free basis, in seven grass species with time. The equations describing this change and r^2 values are given for each species.

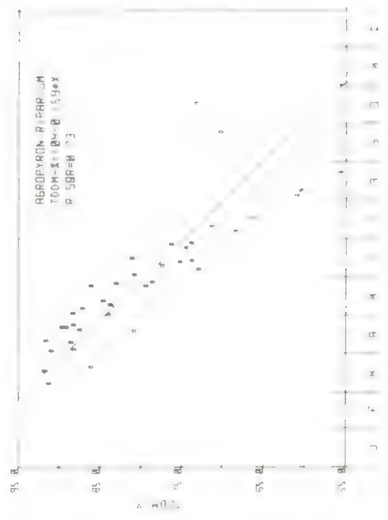

BROMUS TECTORUM
TDDM-%=95-0.09•X
R SQR=0.38
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D


POA SANDBERGII
TDDM-%=100-0.09•X
R SQR=0.57
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D


STIPA COMATA
TDDM-%=97-0.125•X
R SQR=0.65
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D


SITANION HYSTRIX
TDDM-%=107-0.196•X
R SQR=0.7
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D


AGROPYRON DESERTORUM
TDDM-%
R SQR=0.82
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D


AGROPYRON ...PAR...M
TDDM-%=104-0.159•X
R SQR=0.73
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D

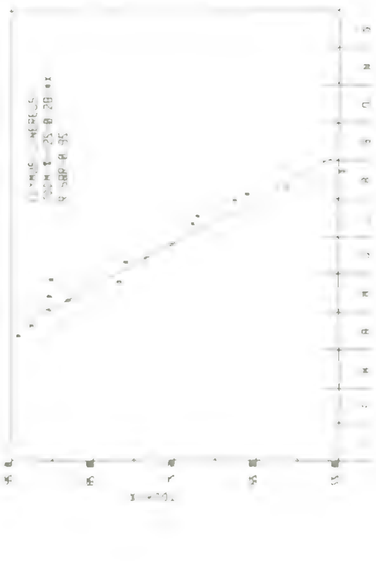

TDDM-%=...25-0.28•X
R SQR=0.95
TDDM-%
95
85
75
65
55
J
F
M
A
M
J
J
A
S
O
N
D

Table 9.--*Comparison of crude protein, calcium, and phosphorus concentrations in cheatgrass (Brte), Sandberg's bluegrass (Posa), and Russian thistle (Saka) on each of four harvest dates*[1]

Date	Crude Protein			Calcium			Phosphorus		
	Brte	Posa	Saka	Brte	Posa	Saka	Brte	Posa	Sak
	Percent								
7-3-69	2.5	2.9	18.4	0.34	0.24	2.2	0.04	0.04	0.28
8-2-69	3.0	2.1	16.7	.37	.14	2.0	.06	.03	.16
8-28-69	3.5	2.2	15.2	.28	.12	1.5	.05	.02	.17
10-3-69	2.8	2.1	7.0	.26	.11	1.3	.03	.02	.17

[1] From M.S. thesis, Olsen, T. E., Univ. Idaho 1971.

Animal Responses

Despite the many negative features of cheatgrass range, including early maturity generally low yields, and high fire hazard, it serves as a valuable forage resource in the western United States. This was shown by Murray (1971) and Murray and Klemmed (1968), who reported details of sheep and cattle grazing studies on the Saylor Creek Experimental Range.

Daily weight gains by yearling cattle stocked at several intensities during earl spring, late spring, summer, and fall seasons, are given in figure 30. As in most grazing intensity studies, individual performance declined as stocking rate increased On cheatgrass range, individual weight gains were most sensitive to changes in stocking rates in early and late spring, corresponding to the green feed period.

Yearling cattle weights over the entire grazing period are shown in figure 31. These data represent weight gains by cattle stocked at all experimental levels from 1961 through 1968. Differences in weight gain are attributed to differences in the quantity and quality of forage, stocking rates, and quality of cattle provided by the different ranchers.

Five years of weight gain data are shown in figure 32 for cows and calves. Cows in the 1974, 1975, and 1976 studies received supplemental crude protein, phosphorus, and sulfur during the mid-June to mid-October period; thus their performance would be better than that expected from unsupplemented animals. First-calf heifers (1972 and 1973) did not gain weight beyond the green feed period, nor did their calves do as we as did the animals in other years. Forage quality was not high enough for the pregna and growing young animals. Also of importance is the decrease in rate of gain by cal after about October 1. Ranchers would be advised to place calves on higher quality feed at this time if rate of gain is to be continued.

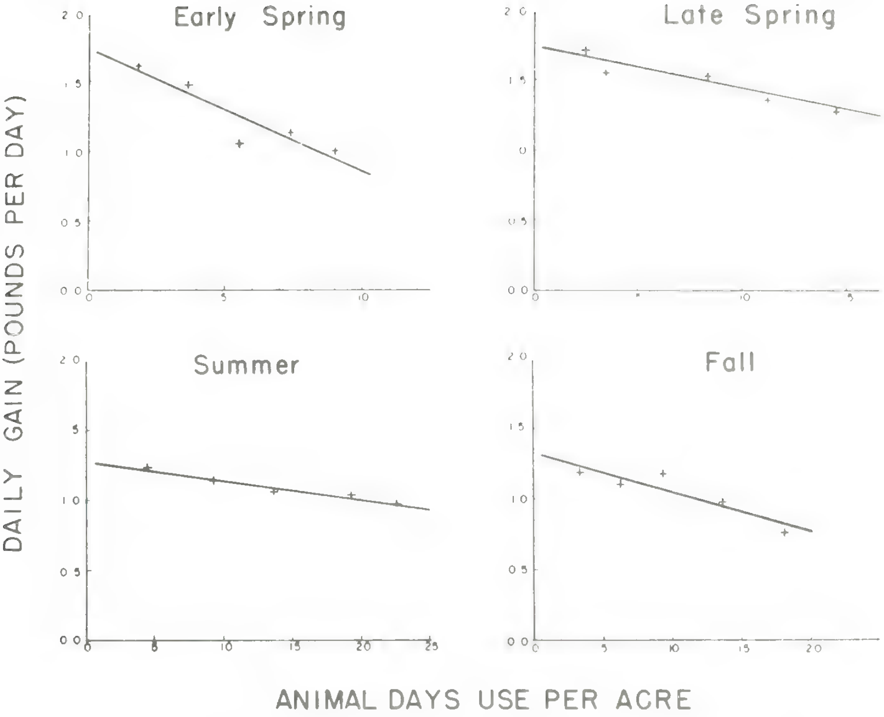


Figure 30.--Daily weight gains by yearling cattle at several stocking intensities on the Saylor Creek Experimental Range during early spring (April 1-May 5), late spring (May 6-June 9), summer (June 10-Sept. [illegible]), and fall [illegible]. [illegible] are means of 5 years of study results ([illegible] through [illegible]). [illegible]

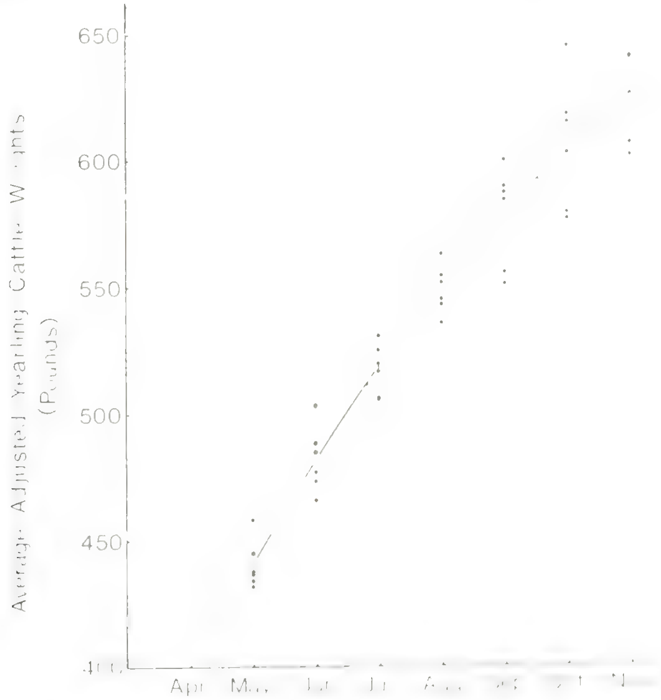


Figure 31.--Yearling cattle weights adjusted to a 400-pound weight over the period 1964 through 1968 at the Saylor Creek Experimental Range. Additional data represented by o and Δ (1969 and 1970, respectively) are shown, but not included in the average response curve.

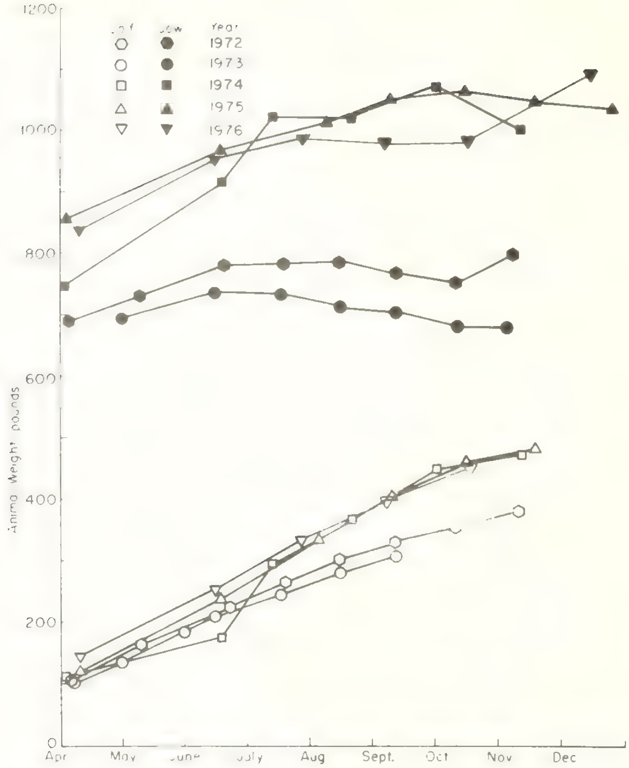


Figure 32.--Cow and calf weights for 5 years at the Saylor Creek Experimental Range. Animal ownership and age of cows varied. Cows in 1972 and 1973 were first-calf heifers. Means are for 100 to 120 animals each year. Note that cattle in 1974, 1975, and 1976 received supplemental crude protein, phosphorus and sulfur during the mid-June through mid-October period.

CONCLUSIONS AND RECOMMENDATIONS

In many areas of the semiarid West, the annual cheatgrass has replaced the longer lived grasses. Normally, cheatgrass germinates in the fall, overwinters, grows rapidly during the spring, and matures by mid-June. Forage quality declines as the forage matures. Consequently, cattle grazing on these ranges are consuming forage of poor quality over most of the grazing season (June to November). We have shown in this study that protein content and many minerals declined to levels below that recommended for optimum livestock performance.

On private cheatgrass range, cattle should be supplemented with both energy and crude protein as the forage matures (fig. 33). Supplementation, except for salting, is not allowed on public rangelands. Supplementing crude protein for economic production in growing animals has been shown to be impractical on desert wheatgrass beyond mid-August at Squaw Butte, south-central Oregon (Turner and Raleigh 1977). Beyond that point an increased supplement level inhibited forage intake. Therefore, both energy and crude protein should be added to cattle diets from mid-June to mid-August or longer if cattle are to continue to maintain good gains. Those interested in finishing animals on range should consult the paper by Turner and Raleigh (1977).

Figure 13.--Supplementing beef cattle [illegible] cheatgrass range.

Phosphorus levels decline rapidly in [illegible] in many
lant species. However, in cheatgrass, which is predominant on many ranges, the
level is lower, but the Ca:P ratio is within the recommended allowance. Where
eeded, P can be added to the diet in salt blocks, however, satisfactory intake may
ot be achieved; so it is better to use other more palatable carriers such as molasses
icks, cottonseed, or soybean meals.

Levels of all trace minerals, except Zn, are adequate for all classes of cattle
upplemental Zn added to cow and calf diets at Saylor Creek Experimental Range
esulted in better gains than those made by nonsupplemented animals. This suggests
hat Zn should be added to the diet when forage Zn levels drop below 10 ppm, which
n cheatgrass range occurs usually by August 1. The supplemental Zn level ought to
rovide 500 mg Zn per cow-day and can be provided in salt (Mayland, unpublished).

Calves, yearlings, and cows do well on cheatgrass range in the early spring
o early summer period. First-calf heifers, which have not attained full growth
equire better feed after this period. Nutritional intake is not sufficient to
aintain the fetus, calf, and herself when the forage is dry. Calf gains are
onsiderably reduced by October 1. First-calf heifers should be placed on better
asture by July, while calves of mature cows would benefit from better feed about
id-September (see also Turner and Raleigh 1977).

Increasing the stocking rate use decreases individual daily gains. The decline
n daily gain is most rapid in the early spring when the forage contains high
oisture and is not always abundant. To obtain maximum daily gains fewer animals
hould be grazed than when optimizing for gains per acre. Because of the extreme

variability in cheatgrass yield between seasons and years, recommending grazing rates is impractical. However, removal of about 60 percent of the available forage will tend to optimize gains per acre.

The use of nitrogen fertilizers to increase yields and/or protein contents of forage on cheatgrass range is not economical. Although, in some years nitrogen additions increase yields up to 4 times those of nonfertilized range, the cost of the fertilizer is prohibitive. In most cases, direct supplementation of energy, protein, and minerals is more practical and cheaper than attempting to improve the forage through fertilization.

Predicting forage yields in advance of the grazing season is desirable. On many perennial grass ranges, this can be done using the accumulated precipitation over the previous winter (Sneva 1977). However, cheatgrass responds more to current precipitation and temperature. Our prediction equation reflects this fact, because April and May precipitation and temperature are included. Use of the equation allows one to estimate the quantity of the forage without extensive harvesting.

Adjusting animal numbers to properly utilize and optimize gains is not readily accomplished, because the rancher in a good year has too few animals while in a poor year he has too many. In those good years, cheatgrass range should be used to relieve pressure from other ranges in poor condition. When forage production is lower than needed on cheatgrass range, animals should be placed on other ranges.

Soil moisture fluctuates with time and depth. The nature of the time-depth curves suggests that deeper rooted plants would benefit from greater moisture lower in the profile that persists over a longer period.

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APPENDIX I

Species referred to in the text

Scientific Name	Common Name
SHRUBS:	
Artemisia tridentata ssp. *tridentata* Nutt.	Basin Big Sagebrush
GRASSES:	
Agropyron desertorum Fisch.	Desert Wheatgrass
Agropyron riparium Schribn. & Smith	Streambank Wheatgrass
Bromus tectorum L.	Cheatgrass, downy brome
Elymus cinereus Schribn. & Merr.	Basin Wildrye
Oryzopsis hymenoides (R & S) Ricker	Indian Ricegrass
Phleum pratense L.	Timothy
Poa sandbergii Vasey	Sandberg's Bluegrass
Sitanion hystrix (Nutt.) Smith	Bottlebrush Squirreltail
Sporobolus airoides Munro	Alkali Sacaton
Stipa comata Trin. & Rupr.	Needle-and-Thread Grass
Stipa thurberiana Piper	Thurber's Needlegrass
FORBS:	
Antennaria dimorpha (Nutt.) T. & G.	Low Pussytoes
Astragalus beckwithii T. & G.	Beckwith's Milk Vetch
Astragalus lentiginosus Dougl.	Specklepod locoweed
Astragalus purshii Dougl.	Pursh Locoweed
Calochortus nuttallii T. & G.	Segolily, Mariposa Lily
Castilleja angustifolia (Nutt.) G. Don	Northwestern Paintbrush
Crepis acuminata Nutt.	Tapertip Hawksbeard
Crepis occidentalis Nutt.	Western Hawksbeard
Descurainia pinnata (Walt.) Britton	Tansy Mustard
Erigeron pumilus Nutt.	Low Fleabane
Eriogonum ovalifolium Nutt.	Oval-Leafed Buckwheat
Lactuca serriola L.	Prickly Lettuce
Lomatium foeniculaceum v. *macdouglii* (Coult. & Rose) Cronq.	Biscuit-Root, MacDougal [illegible]
Lomatium triternatum (Pursh) Coult. & Rose	Nineleaf Lomatium
Microsteris gracilis (Hook.) Greene	Microsteris
Phlox hoodii Rich.	Hood's Phlox
Phlox longifolia Nutt.	Longleaf Phlox
Salsola kali L. v. *tenuifolia* Tausch.	[illegible]
Sisymbrium altissimum L.	[illegible]
Tragopogon sp.	Goats-Beard, Salsify, Oyster Plant

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Bromus tectorum L.	Cheatgrass, downy brome
Elymus cinereus Schribn. & Merr.	Basin Wildrye
Oryzopsis hymenoides (R & S) Ricker	Indian Ricegrass
Phleum pratense L.	Timothy
Poa sandbergii Vasey	Sandberg's Bluegrass
Sitanion hystrix (Nutt.) Smith	Bottlebrush Squirreltail
Sporobolus wrightii Munro	Alkali Sacaton
Stipa comata Trin. & Rupr.	Needle-and-Thread Grass
Stipa thurberiana Piper	Thurber's Needlegrass
FORBS:	
Antennaria dimorpha (Nutt.) T. & G.	Low Pussytoes
Astragalus beckwithii T. & G.	Beckwith's Milk Vetch
Astragalus lentiginosus Dougl.	Specklepod locoweed
Astragalus purshii Dougl.	Pursh Locoweed
Calochortus nuttallii T. & G.	Segolily, Mariposa Lily
Castilleja angustifolia (Nutt.) G. Don	Northwestern Paintbrush
Crepis acuminata Nutt.	Tapertip Hawksbeard
Crepis occidentalis Nutt.	Western Hawksbeard
Descurainia pinnata (Walt.) Britton	Tansy Mustard
Erigeron pumilus Nutt.	Low Fleabane
Eriogonum ovalifolium Nutt.	Oval-Leafed Buckwheat
Lactuca serriola L.	Prickly Lettuce
Lomatium foeniculaceum v. *macdouglii* (Coult. & Rose) Cronq.	Biscuit Root, Macdougal's Lomatium
Lomatium triternatum (Pursh) Coult. & Rose	Nineleaf Lomatium
Microsteris gracilis (Hook.) Greene	[illegible]
Phlox hoodii Rich.	Hood's Phlox
Phlox longifolia Nutt.	Longleaf Phlox
Salsola kali L. v. *tenuifolia* Tausch.	Russian Thistle, Tumbleweed
Sisymbrium altissimum L.	Tumblemustard
Tragopogon sp.	Goat's Beard, Salsify, Oyster Plant

APPENDIX II

Soil descriptions for the needle-and-thread grass and sagebrush sites at Saylor Creek Experimental Range

Needle-and-thread grass site
(NE¼, SE¼, Sec. 17, T.6S., R.9E.)

A11	0-5	Cm--Light brown gray (10 YR 6/2) dry, silt loam, dark gray brown (10 YR 4/2) moist; weak medium platy to weak fine granular; structure weakly coherent, very friable; slightly sticky, slightly plastic; plentiful medium roots; plentiful medium interstitial pores; very slightly effervescent; abrupt, smooth boundary.
A12	5-8	Cm--Light brown gray (10 YR 6/2) dry, silt loam, brown (10 YR 4/3) moist; moderate fine granular to moderate fine platy; structure weakly coherent, very friable, slightly sticky, slightly plastic; plentiful medium roots; plentiful medium tubular pores; slightly effervescent; abrupt, smooth boundary.
C1Ca	8-28	Cm--Light brown gray (10 YR 6/2) dry, silt loam, brown (10 YR 4/3) moist, weak, medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; abundant fine roots; plentiful medium tubular pores; strongly effervescent; clear, smooth boundary.
C2Ca	28-50	Cm--White (10 YR 8/2) dry, fine sandy loam, light brown gray (10 YR 6/2) moist; massive; structure weakly coherent, friable, slightly sticky, nonplastic; plentiful fine roots; plentiful medium tubular pores; violently effervescent; abrupt, smooth boundary.
C3Ca	50-64	Cm--White (10 YR 8/2) dry, fine sandy loam, light brown gray (10 YR 6/2) moist; massive; structure hard, friable, nonsticky, nonplastic; plentiful fine roots; plentiful medium tubular pores; violently effervescent; abrupt, smooth boundary.
IIC4Ca	64-78	Cm--White (10 YR 8/2) dry, sandy loam, light gray (10 YR 7/2) moist; weak coarse platy structure; very hard, very friable, nonsticky, nonplastic, plentiful fine roots; plentiful medium tubular pores; violently effervescent; clear, smooth boundary.
IIC5Casi	78-98	Cm--Pinkish white (7.5 YR 8/2) dry, moderately cemented hardpan, pinkish gray (7.5 YR 7/2) moist; weak coarse platy structure; extremely hard, extremely firm, nonsticky, nonplastic; few fine roots; plentiful medium tubular pores, clear, smooth boundary.
IIC6Casi	98-140	Cm--White (10 YR 8/2) dry, stony hardpan, light gray (10 YR 7/2) moist; weak coarse platy structure; extremely hard, extremely firm, nonsticky, nonplastic, few fine roots; clear, smooth boundary.

Sagebrush

[illegible]

A11	0-7	Cm--Brown (10 YR 5/3) dry, silt loam, dark brown, (10 YR 3/3) moist; weak medium granular structure; slightly hard, very friable, slightly sticky, slightly plastic; plentiful medium roots, plentiful medium pores, slightly effervescent; moderately alkaline (pH 8.0); abrupt, smooth boundary.
B2	7-13	Cm--Yellowish brown (10 YR 5/4) dry, silt loam, dark brown (10 YR 3/3) moist; weak, fine subangular blocky structure; slightly hard, very friable, slightly sticky, slightly plastic; plentiful medium roots; plentiful medium tubular pores; slightly effervescent; moderately alkaline (pH 8.0); abrupt, smooth boundary.
C1Ca	13-31	Cm--Pale brown (10 YR 6/3) dry, silt loam, brown (10 YR 4/3) moist; moderate, fine subangular blocky structure; slightly hard, friable, slightly sticky slightly plastic; plentiful medium roots; plentiful medium tubular pores; violently effervescent; moderately alkaline (pH 8.2); abrupt, smooth boundary.
C2Ca	31-41	Cm--Light gray (10 YR 7/2) dry, silt loam, gray brown (10 YR 5/2) moist; moderately medium platy structure; slightly hard, friable, slightly sticky, slightly plastic; plentiful medium roots; plentiful medium tubular pores; violently effervescent: moderately alkaline (pH 8.2); boundary not given.
C3Ca	41-63	Cm--Light gray (10 YR 7/2) dry, very fine sandy loam, gray brown (10 YR 5/2) moist; weak medium subangular blocky structure; hard, slightly firm; slightly sticky; slightly plastic; plentiful medium roots; plentiful medium tubular pores; violently effervescent; moderately alkaline (pH 8.2) abrupt, smooth boundary.
IC4Ca	63-77	Cm--White (10 YR 8/2) dry, fine sandy loam, light brown gray (10 YR 6/2) moist; moderate, medium angular blocky structure; hard, firm; slightly sticky, nonplastic; plentiful fine roots; plentiful medium tubular pores; violently effervescent; moderately alkaline (pH 8.4); abrupt, wavy boundary.
IIC5Casi	77-112	Cm--White (10 YR/8/2) dry, hardpan, very pale brown (10 YR 7/3) moist; moderate, medium platy structure; very hard, firm, nonsticky, nonplastic; plentiful fine roots; plentiful medium tubular pores; violently effervescent; strongly alkaline (pH 8.6); abrupt, wavy boundary.
IIC6Camsi	112-128	Cm--White (10 YR 8/2) dry, indurated hardpan, very pale brown (10 YR 7/3) moist; strong, coarse platy structure; extremely hard, extremely firm, nonsticky, nonplastic; no roots; plentiful medium tubular pores; violently effervescent; strongly alkaline (pH 8.6); abrupt, wavy boundary.
IIC7Casi	128-140	Cm--White (10 YR 8/2) dry, degraded hardpan, light gray (10 YR 7/2) moist; massive; structure very hard, nonfirm, nonsticky, nonplastic; no roots; abundant medium interstitial pores; violently effervescent; strongly alkaline (pH 8.6); boundary not given.

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are included.

[illegible]

Experimental Range. Samples were analyzed for mineral contents and [illegible]

mates of soil chemical status, soil moisture trends, forage yields and moisture changes, effects of fertilization with ammonium nitrate on for- [illegible]

are included.

[illegible]

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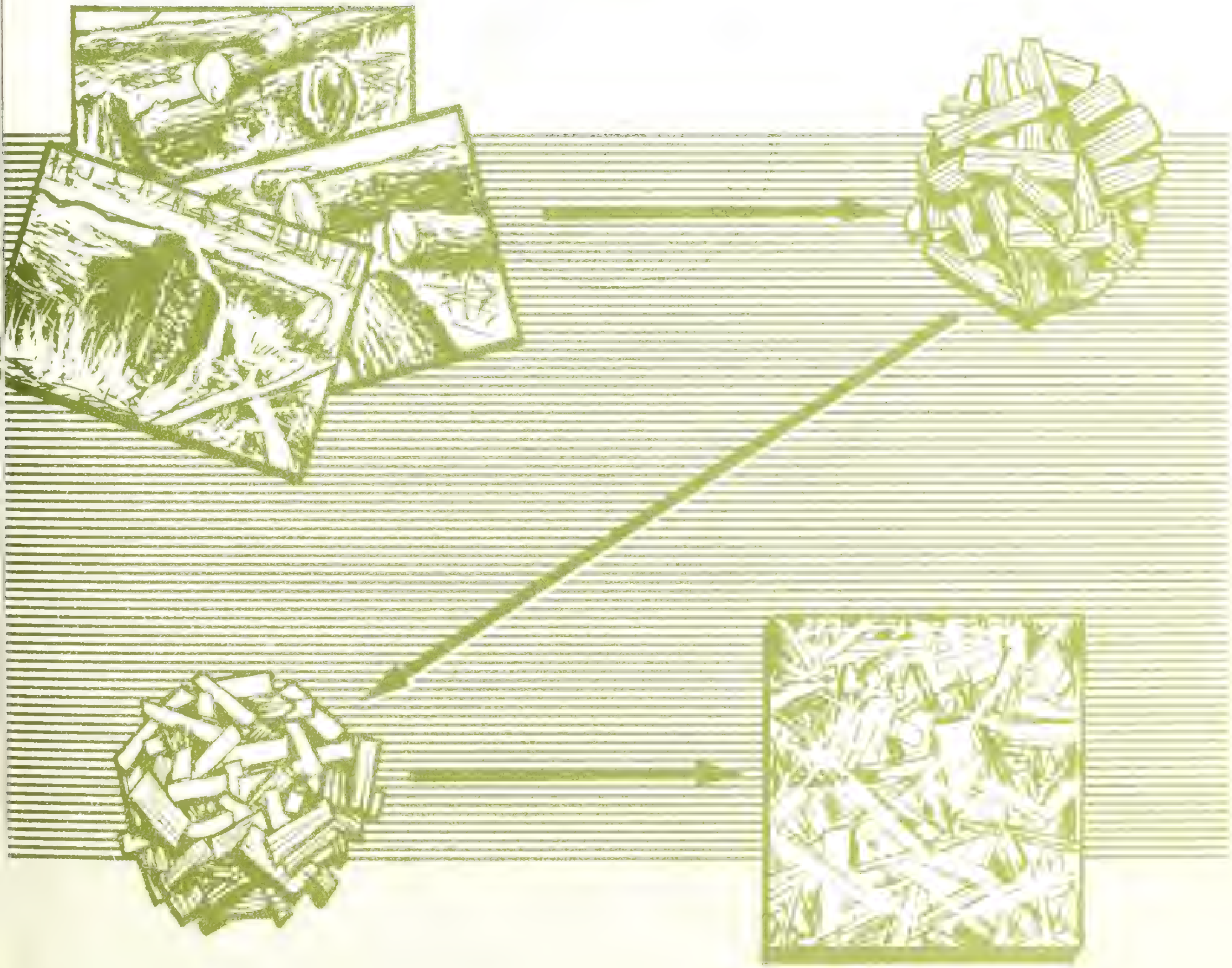
CONVERTING FOREST RESIDUE TO STRUCTURAL FLAKEBOARD —

THE FINGERLING CONCEPT

Rulon B. Gardner,
Erwin L. Schaffer, and
John R. Erickson



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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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RESEARCH SUMMARY

Structural-grade flakeboard experimentally manufactured from forest residues showed mean strengths above 5,500 psi and stiffness (MOE) above 600,000 psi. For economical transport, residues are chipped into "fingerlings" in the woods. Chipping rates are estimated at 50 tons per hour for large residues, and 15 tons per hour for small residues--using different machines. Depending on the harvesting system selected, estimated costs of fingerlings delivered to the mill range from $25 to $33 per bone-dry ton for systems other than cable yarders.

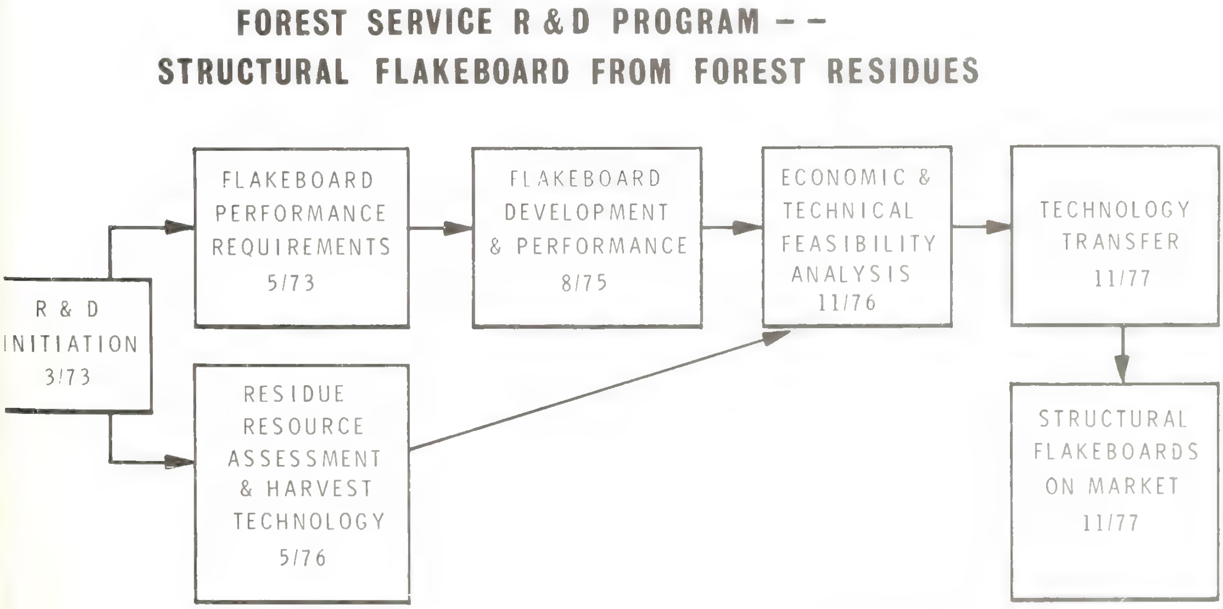
STRUCTURAL FLAKEBOARD RESEARCH AND DEVELOPMENT PROGRAM

More intensive use of forest residue has long been the goal of forest managers.
n estimated 9 billion cubic feet of residue is left in the woods annually. Of this
mount, an estimated 6 billion cubic feet could be converted to particleboard, flake-
oard, pulp, fuel, and other uses. Increased use of residues would greatly extend the
imber supply and generally improve forest management.

Converting forest residues to structural-grade flakeboard has been under consider-
tion for many years. However, several problems remained unsolved. The flaking
achines available were designed for use at mills and were too cumbersome and too easily
nocked out of tolerance to be used at logging sites. Residues other than cull logs were
oo bulky to haul to the mills economically. Trucks would overflow with small, crooked
tems, limbs, and chunks when loaded to only a small fraction of weight capacity.

A concept that had shown promise in the laboratory was the breaking of residues into
mall pieces called "fingerlings," then flaking the fingerlings with a small laboratory
laking machine, and finally manufacturing the flakes into flakeboard. Theoretically,
eside could be converted to fingerlings on the logging site and transported to the mill
uch more economically than the raw residues. Whether the fingerling concept would
ork on a commercial scale remained to be tested.

Early in 1973, the Forest Service began a research and development program to con-
ert residues into structural flakeboard. Three Experiment Stations, four Divisions
f the Washington Office, and the Forest Products Laboratory were involved (fig. 1).


FOREST SERVICE R & D PROGRAM --
STRUCTURAL FLAKEBOARD FROM FOREST RESIDUES
R & D INITIATION 3/73
FLAKEBOARD PERFORMANCE REQUIREMENTS 5/73
FLAKEBOARD DEVELOPMENT & PERFORMANCE 8/75
ECONOMIC & TECHNICAL FEASIBILITY ANALYSIS 11/76
TECHNOLOGY TRANSFER 11/77
RESIDUE RESOURCE ASSESSMENT & HARVEST TECHNOLOGY 5/76
STRUCTURAL FLAKEBOARDS ON MARKET 11/77

igure 1.--Forest Service program to develop structural flakeboard from forest residue.

The Intermountain Station was to develop systems for harvesting western softwoods. The North Central Station was to develop machinery that could convert residues to fingerlings. The Forest Products Laboratory was to work out techniques for manufacturing flakeboard from fingerlings.

This report covers progress in the research and development program through the Flakeboard Development and Performance phase shown in figure 1. The report describes fingerling production from large and small residues, systems and costs for harvesting residues, the manufacturing of structural flakeboard, and configuration and performance of experimental panels.

THE FINGERLING CONCEPT

A fingerling is a piece of wood approximately 2 to 3 inches long, with a cross section of less than 1 by 1 inch (fig. 2). Fingerling production is the first step in producing flakes for structural flakeboard. The first flakes used for structural flakeboard were manually split from blocks 2.5 inches long. Later experiments used laboratory disk flakers to produce flakes.

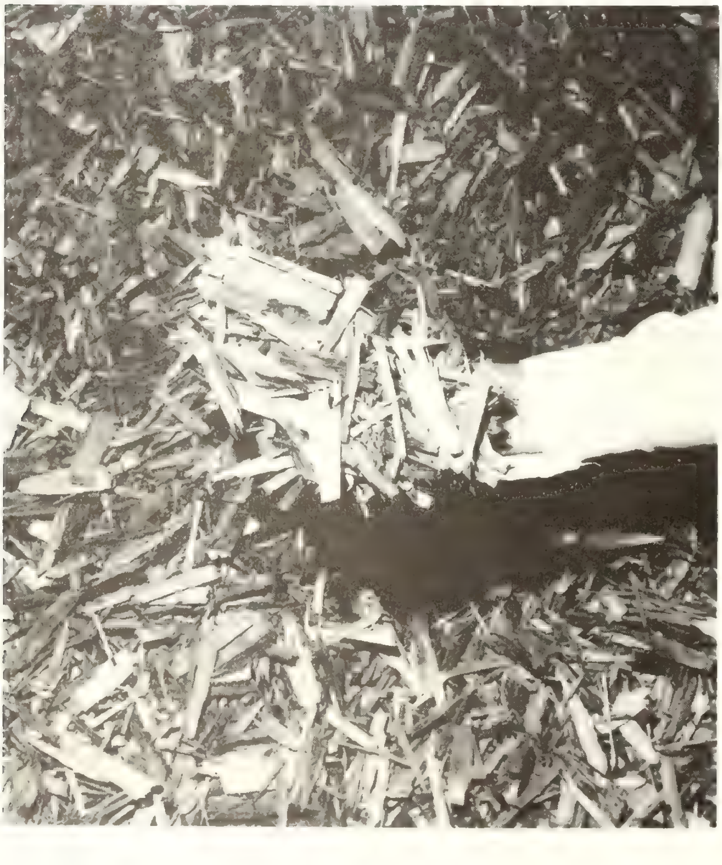


Figure 2.--Fingerlings: the first step in converting residue to flakeboard.

The Research and Development (R&D) team recognized early the need for mechanization of fingerling and flake production. Different size classes of residue by geographical sections of the country suggested that the problem of reducing residues to fingerling chips be split for research assignment. The North Central Station pursued the problem of chippping the smaller residues, while the Forest Products Laboratory sought out equipment for chipping larger residues.

Small Residue

The North Central Station found that conventional chippers produced chips that varied too much in length to make suitable fingerlings. This led to the invention of a spiral head chipper (fig. 3). Although this machine would cut 95 percent or more of the pieces to the length set by the cutter, many exceeded the 1- by 1-inch cross section required for fingerlings. A hammermill with the grates removed reduced the oversized pieces to finger-sized particles in one pass. The structural flakeboard made from the aspen and spruce had very good strength (Erickson 1976).

The similar problem of oversized fingerlings occurred when lodgepole pine, Douglas-fir, and larch were chipped for this study. Hammermilling was needed to reduce chips to fingerling size. Redesigning the blades in the spiral head chipper may eliminate the need for hammermilling.

Conventional drive-shaft-mounted strain-gaging methods were used to measure torque over cutting time and hence specific horsepower requirements by species. The western species chipped required slightly higher horsepowers than Michigan-cut wood based on specific gravities (table 1), perhaps because of the low moisture content of the western wood. Power requirements, although a little higher than with conventional chippers,

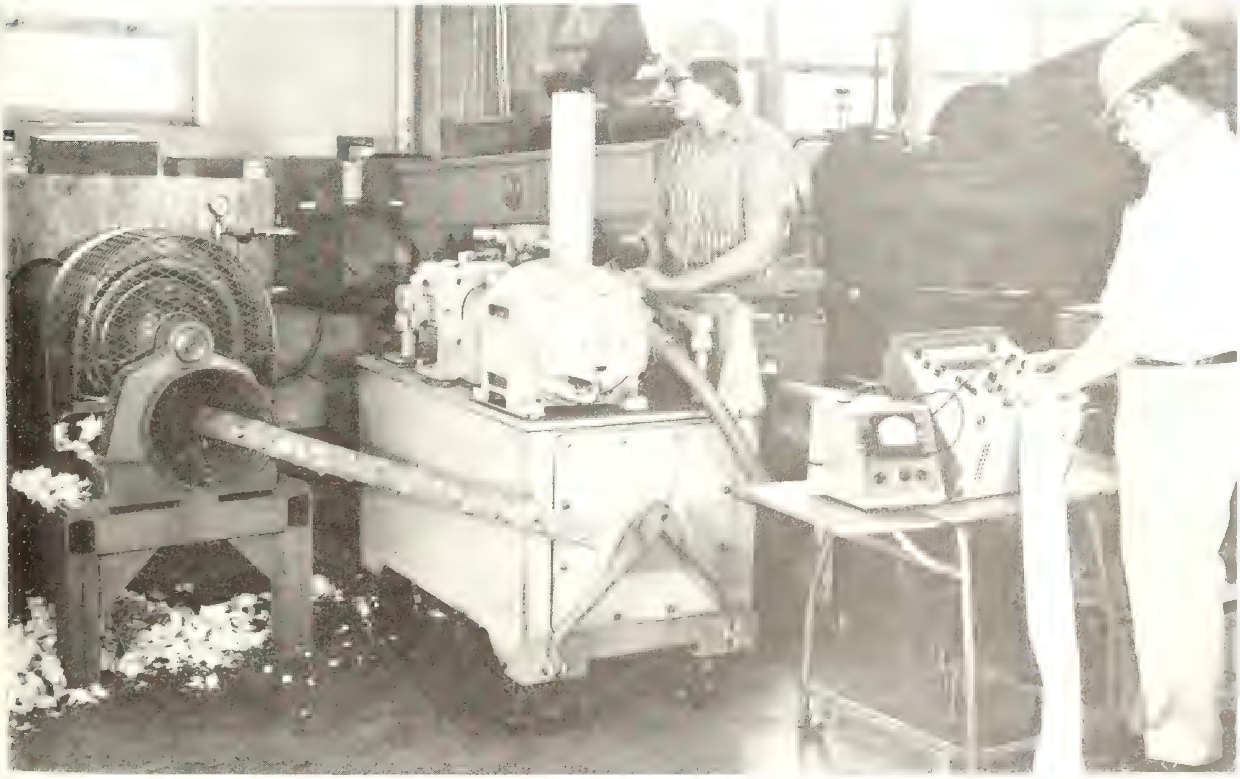


Figure 3.--Fingerling production using the spiral head chipper.

Table 1.--*Power requirements for producing fingerling chips with the Forest Service spiral head chipper*

Species	No. sample	Specific gravity	Specific power
			$\frac{Hp/min}{ft^3}$
Lodgepole pine	12	0.413 - 0.466	8.7
Douglas-fir	1	-	8.1
Larch	8	.492 - .515	9.2
Aspen	8	.343 - .377	5.2
Basswood	7	.278 - .318	5.2
Red oak	6	.510 - .549	9.3
Sugar maple	3	.618 - .658	15.1

could be met by portable units. Envisioned are field operations similar to whole-tree chipping operations now commonly producing pulpwood chips.

A conceptual field unit is shown in figure 4. A portable unit can be constructed for an estimated $35,000. Using a 6-year life, straight-line depreciation, and 15 percent interest and contingency rates, the hourly operating cost is estimated at $12.48. Based on an average 6-inch-diameter log and 60 percent feed rate, production is estimated to be 15 tons per hour (table 2).

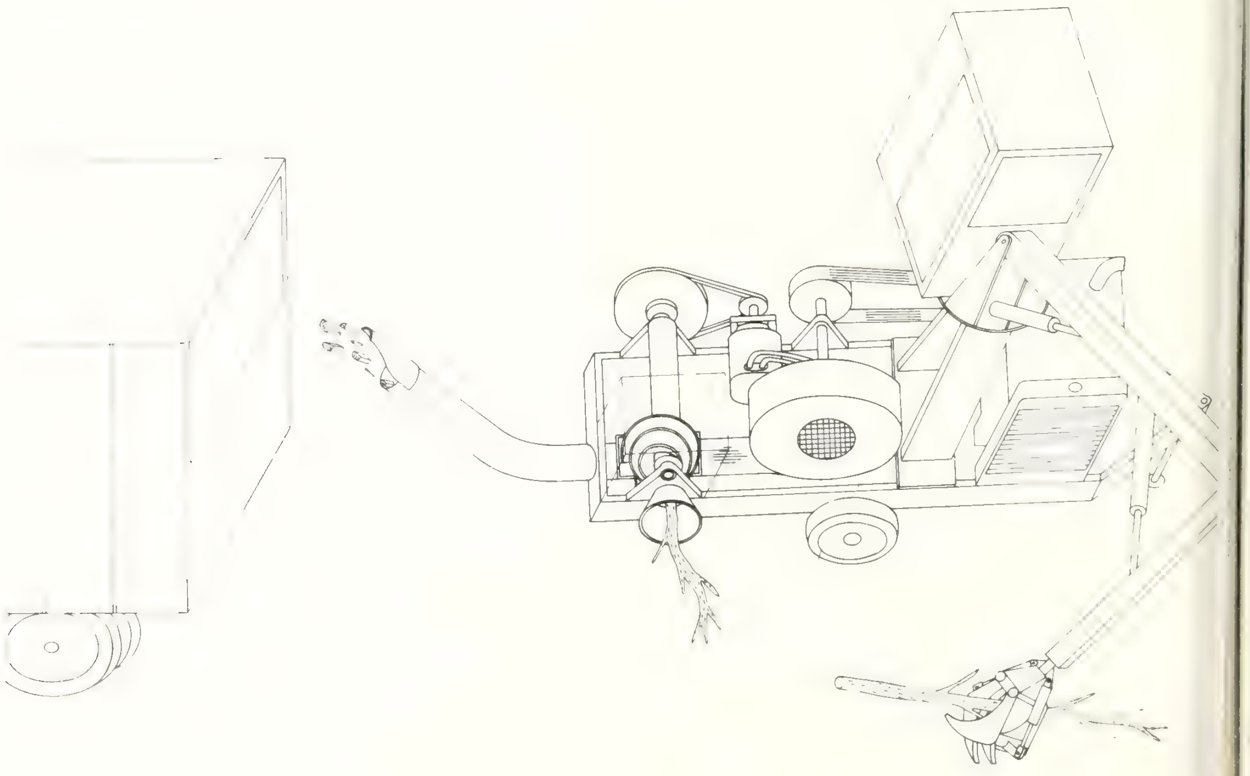


Figure 4.--Concept of mobile unit for producing fingerlings.

Table 2.--*Fingerling production by operating speed and log diameter*

Log diameter (inches)	Cutter head R/min		
	300	350	400
	Cubic feet per minute		
4	5.5	6.5	7.5
6	12.0	14.0	16.0
8	21.5	25.0	28.5
10	34.0	40.0	46.0

Large Residue

The Arasmith Manufacturing Company drum chipper was chosen for chipping large residues. A contract resulted in a modified drum chipper with special knives to cut chips 2 1/2 inches long (fig. 5). This chipping process required cutting the residues to the length of the drum and feeding the log axially parallel to the axis of the drum. The primary drawback is having to cut residues to a specified length. The principal advantage is that when chips are cut parallel to the axis of the log, horsepower consumption is not highly sensitive to log diameter. When the knives cut through the diameter of the log, large horsepowers are needed for larger logs because the cutting power increased proportional to the square of the log diameter. The modest horsepower required by the drum chipper will allow use of relatively low-powered units suited to in-the-woods chipping. The manufacturer estimates that a 42-inch-diameter, 60-inch-long drum chipper making 3/8-inch-thick fingerlings can be driven with a 200-hp diesel engine. Its output could be about 50 tons per hour of operation when fully loaded.

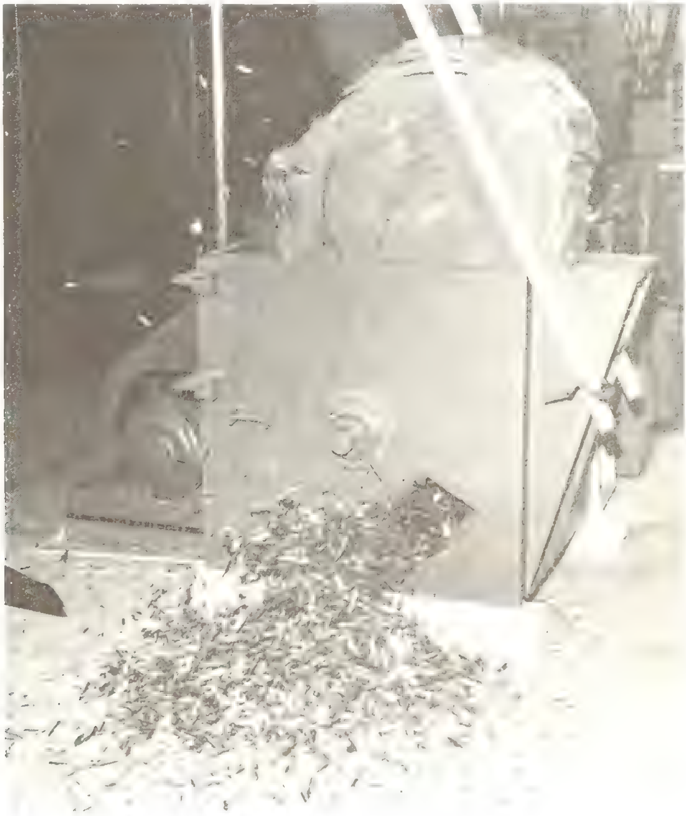


Figure 5.--*Modified drum chipper.*

HARVESTING SYSTEMS FOR RESIDUE

Research suggests that the most efficient time to harvest logging residue is in conjunction with the commercial harvesting, especially when clearcutting, because the entire tree can usually be removed in one operation. An alternative method is to remove part or all of the residue after commercial harvesting.

Previous studies of clearcutting in gentle terrain and near-complete removal of the fiber indicate that this method will be most economical for residue harvesting. This is true, of course, for almost any harvesting method comparisons.

Methods and Equipment

Figure 6 shows six systems for near-complete harvesting of relatively small-size timber averaging 10-ft^3 piece size. Equipment for each system is shown in figure 7. In a study of intensive utilization in lodgepole pine in Wyoming, merchantable and nonmerchantable (residue) volumes were nearly equal. (This probably represents a slightly less than normal volume of residue typical for lodgepole pine, but somewhat greater than normal for most other species in the Rocky Mountain West.)

Following is an example of the volume and classification of material from the Wyoming study (Gardner and Hann 1972). Description of unit 1 before and after harvesting:

Areas of unit (acres) - 16.8
Average stand age - 168.7
Average site index (50-yr base) - 43.7
Volume/acre to 6-inch top of live standing trees (ft^3) - 5,912
Volume/acre to 6-inch top of dead standing trees (ft^3) - 1,014
Total volume/acre to 6-inch top (ft^3) - 6,926 (±621)*
Volume/acre of tree residuals**(ft^3) - 1,124(±205)
Volume/acre of ground material $\leq$ 3 inches in size (ft^3) - 1,820(±308)
Preharvest total volume/acre of (ft^3) - 9,870(±723)
Postharvest volume/acre of ground material $\leq$ 3 inches (ft^3) - 564(±118)

* Figures in parentheses are 68-percent confidence intervals.

** Tree residuals are the difference between total volume for trees 3.0 inches d.b.h and larger, and merchantable volume to a 6-inch top for trees 6.5 inches d.b.h. and larger.

Many combinations of equipment with different levels of mechanization could be designed for harvesting 10 ft^3 (total tree volume, merchantable and nonmerchantable) average timber size used in the simulation trials. Trials were therefore limited to tests of representative equipment types that would either singularly perform subsyste operations or combine them: felling, limbing, lopping, skidding, loading, hauling, felling-bunching, felling-skidding, limbing-lopping, felling-limbing-lopping-bunchin Other subsystem operations are performed as needed in each system shown in figure 7.

Because simulation does not produce an optimum system, the trials in this repor are only to show possible methods of near-complete harvesting and their relative cos A list of equipment for each operation and estimated production data are given in table 3. The special harvesting or processing equipment is shown in appendix A.

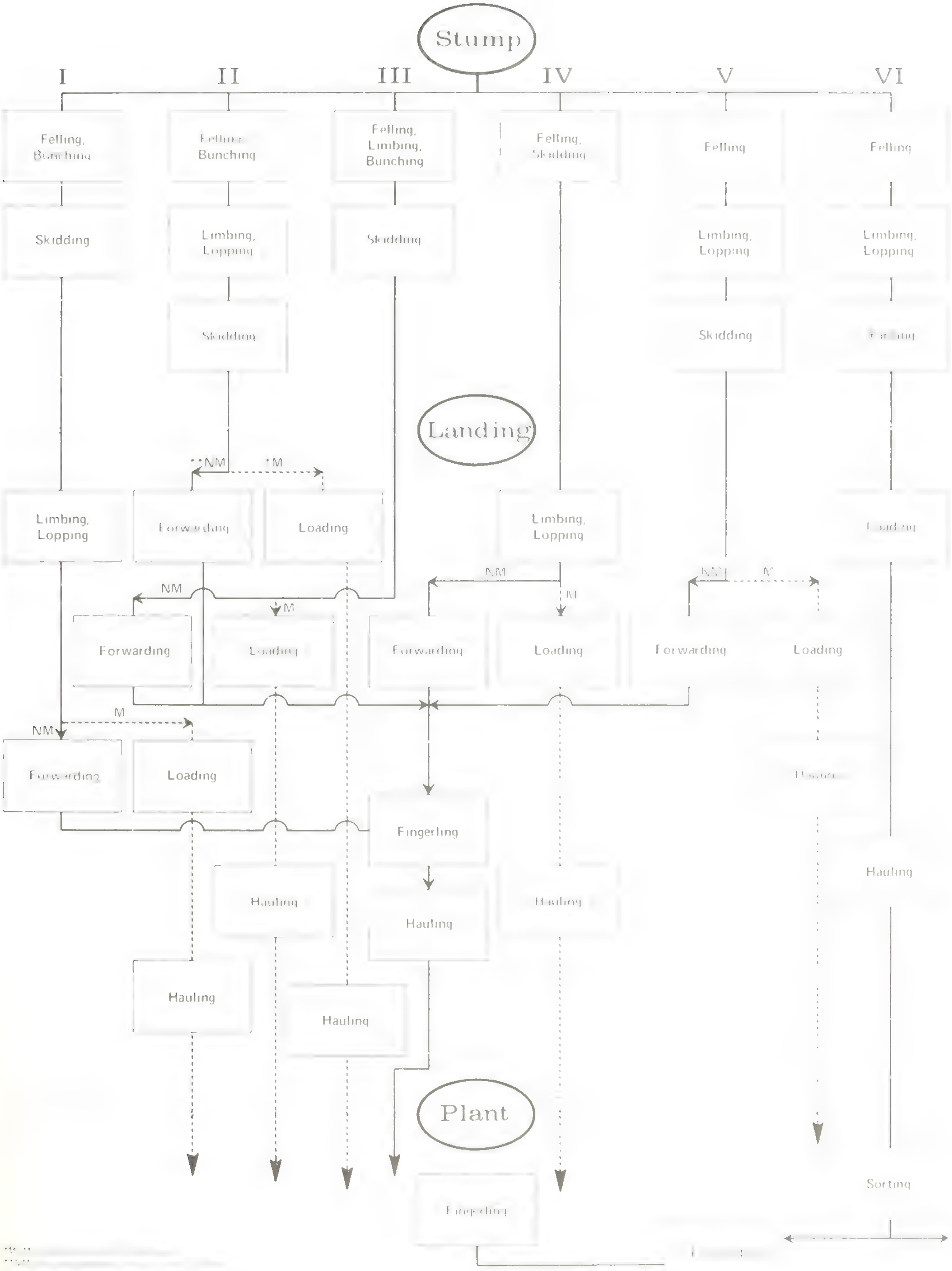
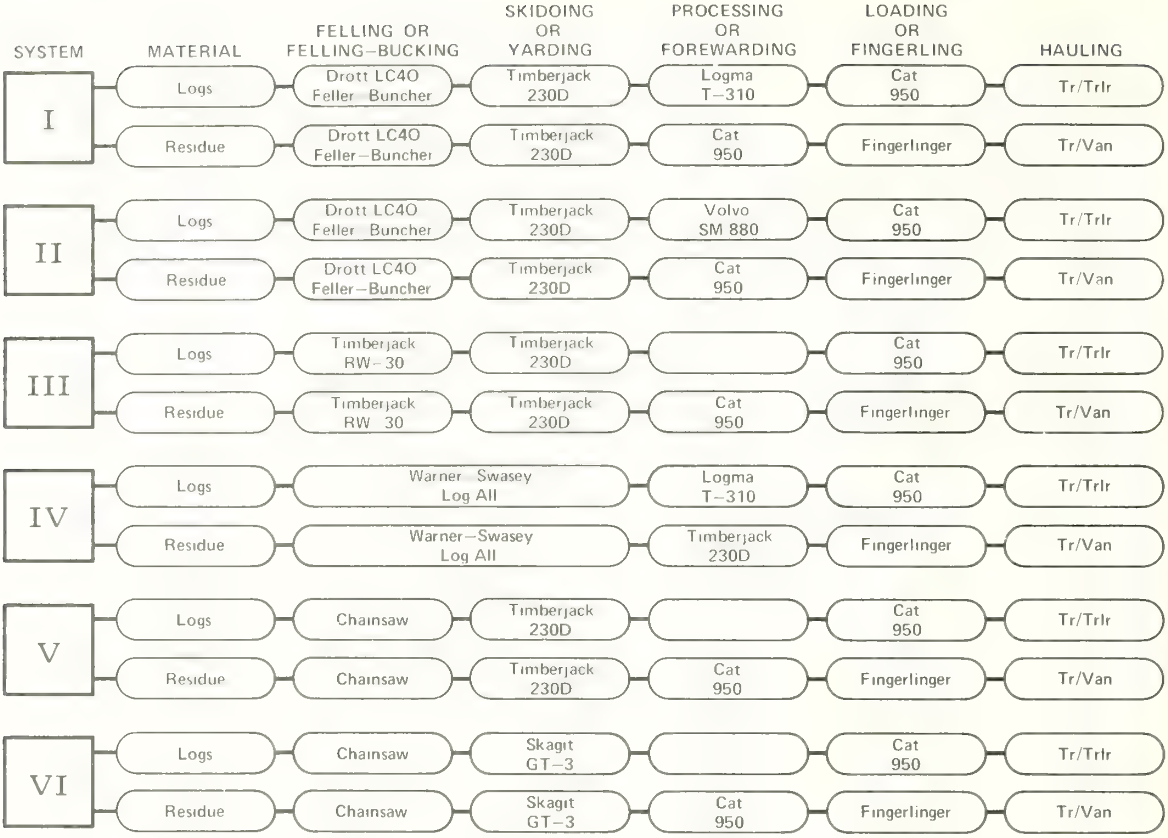


Figure 6.—[illegible] systems.



SYSTEM	MATERIAL	FELLING OR FELLING–BUCKING	SKIDDING OR YARDING	PROCESSING OR FOREWARDING	LOADING OR FINGERLING	HAULING
I	Logs	Drott LC40 Feller Buncher	Timberjack 230D	Logma T–310	Cat 950	Tr/Trlr
	Residue	Drott LC40 Feller–Buncher	Timberjack 230D	Cat 950	Fingerlinger	Tr/Van
II	Logs	Drott LC40 Feller Buncher	Timberjack 230D	Volvo SM 880	Cat 950	Tr/Trlr
	Residue	Drott LC40 Feller–Buncher	Timberjack 230D	Cat 950	Fingerlinger	Tr/Van
III	Logs	Timberjack RW–30	Timberjack 230D		Cat 950	Tr/Trlr
	Residue	Timberjack RW 30	Timberjack 230D	Cat 950	Fingerlinger	Tr/Van
IV	Logs	Warner Swasey Log All		Logma T–310	Cat 950	Tr/Trlr
	Residue	Warner–Swasey Log All		Timberjack 230D	Fingerlinger	Tr/Van
V	Logs	Chainsaw	Timberjack 230D		Cat 950	Tr/Trlr
	Residue	Chainsaw	Timberjack 230D	Cat 950	Fingerlinger	Tr/Van
VI	Logs	Chainsaw	Skagit GT–3		Cat 950	Tr/Trlr
	Residue	Chainsaw	Skagit GT–3	Cat 950	Fingerlinger	Tr/Van

Figure 7.--Equipment for alternative harvesting systems.

Table 3.--*Operation, equipment type, and estimated production rates (piece size 10 ft^3, availability 75%; 40-mile haul)*

Operation	Equipment	Production rate
		Ft^3/h
Felling	Chainsaw	390
Limbing, bucking	Chainsaw	310
Felling, bunching	Drott Feller Buncher LC-40	1,480
Limbing, lopping	Volvo SM880 Processor	2,000
Limbing, lopping	Logma T-310	900
Skidding	Grapple Skidder Timberjack 230D	600
Yarding	Skagit Gt-3 Running Skyline	400
Loading	Front End-Cat 950	1,800
Loading	Knuckle Boom Drott LC-40	1,000
Forwarding	Front End Loader Cat 950	1,500
Chipping	Fingerling Chipper	600
Felling, limbing, bunching	Timberjack RW-30 Tree-length Harvester	500
Log hauling	Truck and trailer (6,000 m bd. ft)	320
Fingerling hauling	Truck and trailer (15 unit)	320
Felling, skidding	Warner-Swasey Log-All	200

In tables 4 through 9, the equipment and number of units needed to balance each ystem were tentatively designed for simulation trials. In every system, the harvested aterial is assumed to be a 50-50 mix of merchantable and residue material. For ystem VI, all of the harvested material is transported to the mill for sorting and the ingerlings are manufactured at the plant. For all other systems (fig. 7), the fingerings are made at the landing and transported to the mill along with the merchantable ogs. The logs and fingerlings are not necessarily transported to the same location, ut for this report, they are transported the same distance: 40 miles.

Table 4.--*Sustem I*

Operation	Equipment	No. units	Unit production	Total production
			Ft^3/h	
Felling, bunching	Drott Feller Buncher	1	1,500	1,500
Skidding	Timberjack 230D	3	600	1,800
Limbing, lopping	Logma T-310	2	900	1,800
(750 ft^3 residue)				
Forwarding	Cat 950	1	1,500	1,500
Fingerling		1	600	600
Hauling	Truck and trailer	2	320	640
(750 ft^3 merchantable)				
Loading	Cat 950	1	1,800	1,800
Hauling	Truck and trailer	2	320	640

Table 5.--*System II*

Operation	Equipment	No. units	Unit production	Total production
			Ft^3/h	
Felling, bunching	Drott Feller Buncher	1	1,500	1,500
Limbing, lopping, bunching	Volvo 880	1	2,000	2,000
Skidding	Timberjack 230D	3	600	1,800
(750 ft^3 residue)				
Fingerling		1	600	600
Hauling	Truck and trailer	2	320	640
(750 ft^3 merchantable)				
Loading	Cat 950	1	1,000	1,000
Hauling	Truck and trailer	2	320	640

Table 6.--*System III*

Operation	Equipment	No. units	Unit production	Total production
			Ft³/h	
Felling, limbing bunching	Timberjack RW-30 Tree-length Harvester	2	500	1,000
Skidding	Timberjack 230D	2	600	1,200
(500 ft³ residue)				
Forwarding	Cat 950	1	1,500	1,500
Fingerling		1	600	600
Hauling	Truck and trailer	2	320	640
(500 ft³ merchantable)				
Loading	Cat 950	1	1,800	1,800
Hauling	Truck and trailer	2	320	640

Table 7.--*System IV*

Operation	Equipment	No. units	Unit production	Total production
			Ft³/h	
Felling, skidding	Warner-Swasey	6	200	1,200
Limbing, lopping	Logma T-310	2	900	1,800
(600 ft³ residue)				
Forwarding	Timberjack 230D	1	1,500	1,500
Fingerling		1	600	600
Hauling	Truck and trailer	2	320	640
(600 ft³ merchantable)				
Loading	Cat 950	1	1,000	1,000
Hauling	Truck and trailer	2	320	640

Table 8.--*System V*

Operation	Equipment	No. units	Unit production	Total production
			---Ft³/h---	
Felling	Chainsaw	3	390	1,170
Limbing, lopping	Chainsaw	4	310	1,240
Skidding	Timberjack 230D	2	600	1,200
(600 ft³ residue)				
Forwarding	Timberjack 230D	1	1,500	1,500
Fingerling		1	600	600
Hauling	Truck and trailer	2	320	640
(600 ft³ merchantable)				
Loading	Knuckle Boom	1	1,000	1,000
Hauling	Truck and trailer	2	320	640

Table 9.--*System VI*

Operation	Equipment	No. units	Unit production	Total production
Felling	Chainsaw	3	390	1,170
Limbing, lopping	Chainsaw	4	310	1,240
Yarding	Skagit GT-3	3	400	1,200
Loading	Knuckle Boom	1	1,000	1,000
Hauling	Truck and trailer	4	320	1,280
Sorting	Knuckle Boom	1	1,000	1,000
Forwarding	Cat 950	1	600	600
Fingerling		1	600	600

The approximate production rates in table 3 show relative production capacities and are for tentatively balancing the system. The best production data available are used for each simulation run. Published production data from the Pulp and Paper Research Institute of Canada (PPRIC) were used for most of the processors or harvesters Other production data are from published or unpublished studies of the Forest Engineering research work unit at Bozeman, Montana.

Simulation

The simulation program (SAPLOS) used was developed by Leonard Johnson and others (1972). It was reprogramed from GASP II to GASP IV and adapted for more general use.

Table 10 presents the harvesting and transportation cost per cubic foot for each subsystem for merchantable and nonmerchantable material. The method for computing equipment operating cost for the simulation runs is shown in appendix B. The costs include delay time, but not nonproductive time or overhead cost.

Simulation is a technique to examine alternatives. Field operations could vary considerably from the simulation trials because of such factors as unfamiliarity with the system (in the short run), differences in equipment operators, conditions differing from those under which the data were derived, and other variables. However, the trials are well within the accuracy needed to show the general viability of these systems for clearcut harvesting.

Harvesting systems I-IV are completely mechanized and are usable for the relative flatter terrain in the Rocky Mountain area. Most of the material harvested with these systems would be lodgepole pine, which makes up 29 percent of the commercial species volume in the Northern Rocky Mountain area.

In table 11, the estimated delivered costs including nonproductive time and overhead are shown.

Table 10.--*Costs for simulated alternative harvesting systems ($/ft^3)*

System	Material	Felling or felling and bucking	Skidding or yarding	Processing or forwarding	Loading or fingerling	Hauling	Subtotal	Total
I	Logs	0.0151	0.0291	0.0535	0.0706	0.1081	0.2763	0.483
	Residue	.0151	.0300	.0384	.0614	.0623	.2072	
II	Logs	.0229	.0457	--	.0709	.1105	.2500	.515
	Residue	.0229	.0457	.0581	.0731	.0656	.2654	
III	Logs	.0151	.0291	.0748	.0706	.1081	.2977	.505
	Residue	.0151	.0300	.0384	.0616	.0623	.2074	
IV	Logs	0.1092		.0483	.0718	.1101	.3457	.604
	Residue	.1092		.0253	.0618	.0627	.2590	
V	Logs	.0210	.0454	--	.0706	.1098	.2468	.502
	Residue	.0210	.0441	.0531	.0731	.0646	.2559	
VI	Logs	.0210	.1575	--	.0709	.1100	.3594	.711
	Residue	.0210	.1575	.0384	.0725	.0630	.3524	

Table 11.--[illegible]
(NPT = nonproductive time, OH = payroll cost.)

System	$/dry ton (1973 cost)	Adj. 40% for NPT and OH	Adj. to 1975 cost
I	15.21	21.23	25.48
II	19.48	27.27	32.72
III	15.22	21.31	25.57
IV	19.01	26.61	31.93
V	18.78	26.39	31.67
VI	25.86	36.20	43.44

MANUFACTURING STRUCTURAL FLAKEBOARD FROM FINGERLINGS

Structural flakeboard is an exterior grade panel for use as construction sheathing and is one of the newer entries into the reconstituted wood panel products field. Generally, it is a panel whose surfaces are mainly composed of long, thin flakes (about 1.5 to 3.0 inches long and 0.020 inch thick) bonded together with a weather-resistant or highly durable resin.

Several years ago, researchers at the Forest Products Laboratory showed fingerlings would provide excellent furnish for ring flakers to produce the flakes for structural flakeboard (fig. 8, 9) Heebink and Dominick 1971; Heebink 1972).

Panel Performance Requirements

Structural flakeboard must have three key properties not required in particleboards commonly employed as furniture and floor underlayment: (1) durability, (2) dimensional stability in width and length, and (3) capability to carry building loads even under adverse environmental conditions. Common particleboards have been primarily designed as "gap fillers" or to have a smooth surface; hence, structural properties were not optimized.

Because weather resistance was not sought, conventional boards were constructed with urea resin, which is not as resistant to water or weather as the phenolic resin employed in exterior grades of plywood. Phenolic resin, or a similarly durable resin, should be employed in structural flakeboard.

Exterior-grade plywood meets or even exceeds the performance desired for sheathing. Although structural flakeboards meeting U.S. and Canadian standards are generally inferior in physical properties to structural plywood of equal thickness, phenolic flakeboards are being used as building sheathing, floor underlayment, and cladding (Canadian Standards Association 1975) in Canada. Canadian aspen flakeboard has recently been

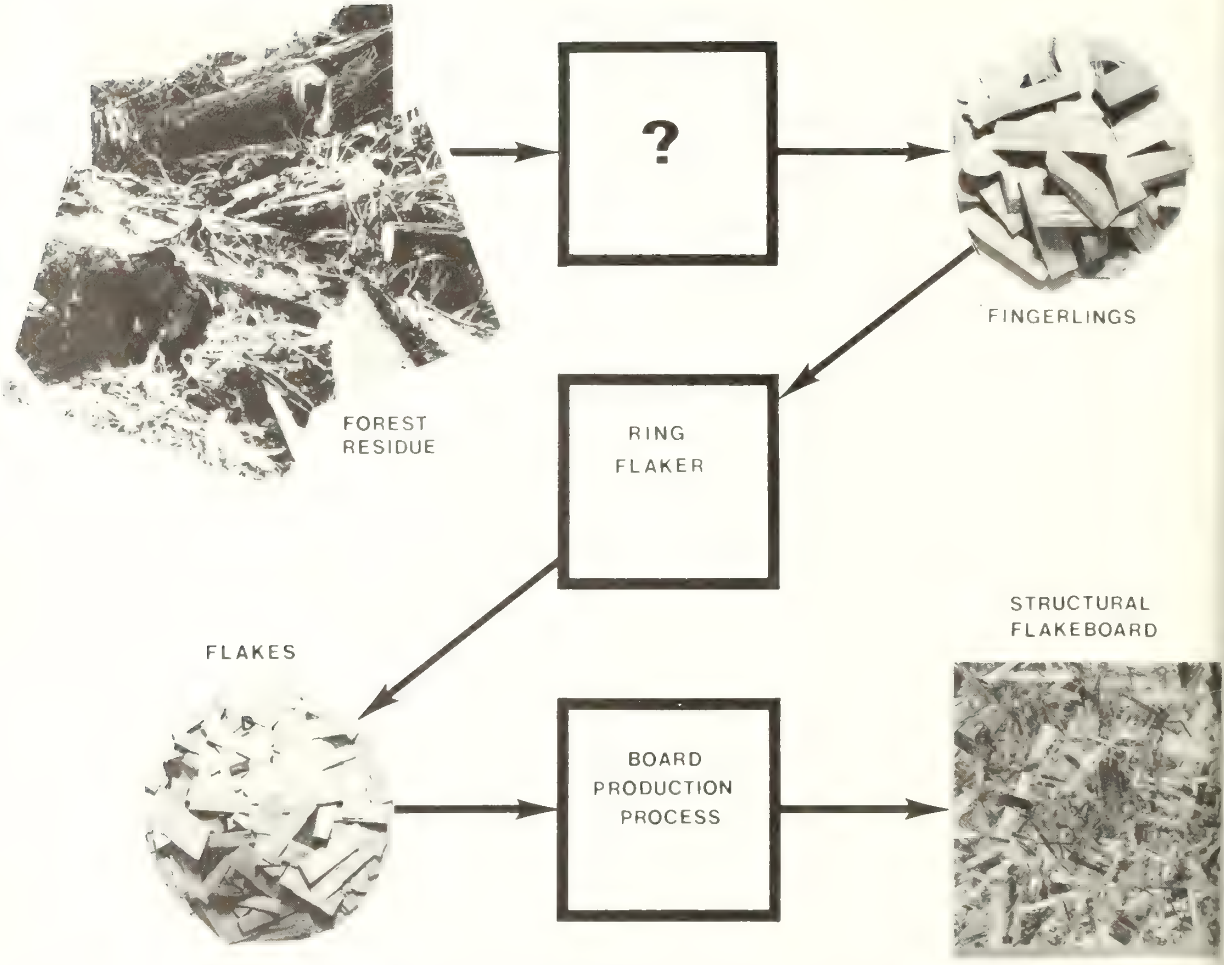


Figure 8.--Fingerling concept for converting forest residues to structural flakeboard

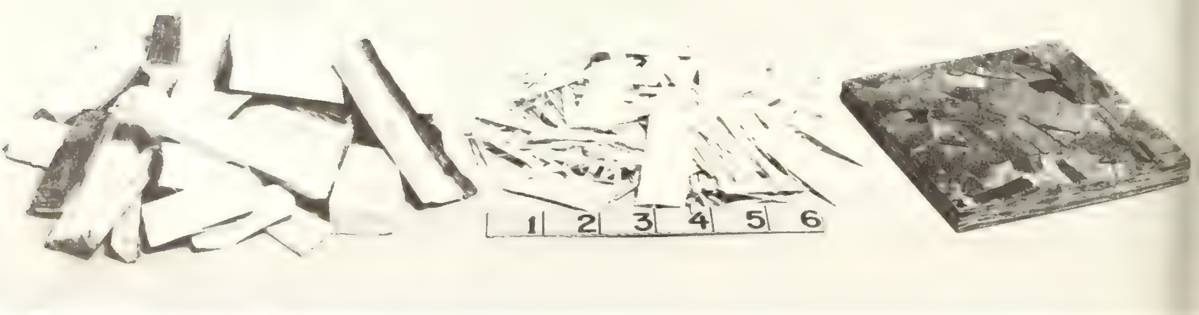


Figure 9.--Fingerlings from spiral chipper, ring flakes, and board.

Table 12.--*Structural flakeboard requirements contained in United States and Canadian standards (minimum average values)*

Requirements	U.S.A.	Canada
Standard	CS 236-66	CSA 0188-1975
Type	2-B-2	Grade P & Q
Density (lb/ft^3)	37 to 50	Not specified or not applicable
Thickness tolerance (± in)	0.016	0.030 - 0.015
Modulus of rupture (lb/in^2)	2,500	2,000
Modulus of elasticity (lb/in^2)	450,000	400,000
Internal bond (lb/in^2)	60	40
Linear expansion (percent) (maximum average 50%-90% RH)	0.25	0.25
Screw-holding strength (lb)		
Face	250	Not specified
Edge	200	Not specified
Residual bending strength after accelerated aging (percent of initial)	50	50

onsidered suitable for roof and wall sheathing in the U.S. (HUD-FHA 1975). The U.S. tandard (U.S. Department of Commerce 1966) does not specify end use for such boards, ut the National Particleboard Association (1970) has obtained recognition of such roperties for these panels to be used as decking (subfloor-underlayment combination) n mobile homes and factory-built housing. One U.S. manufacturer has obtained recogniion of his product by the International Conference of Building Officials (ICBO 1972) s a satisfactory alternative material to that specified in the Uniform Building Code or roof, wall, and floor sheathing and underlayment. Hence, cities and States using he Uniform Building Code would allow use of this board in buildings. The Canadian nd U.S. National Particleboard Association standards currently specifying physical roperty levels for structural flakeboards are shown in table 12. To guide the Forest ervice Program, service load severity and panel properties (table 13) were established. single structural flakeboard having an average MOE (modulus of elasticity) of 725,000 o 800,000 psi and near-minimum MOR (modulus of rupture) of 4,500 psi could meet load arrying requirements for equivalent thicknesses of plywood: the use of 5/8- to 3/4-inch ingle layer floor and 1/2-inch plywood roof sheathing is common (Countryman 1975).

Board Configurations

Defining the physical properties in structural panels poses the problem of selectng board configurations to meet requirements at reasonable or competitive cost. The anadians have had excellent success with a panel composed of randomly oriented flakes, ither placing the best quality flakes on the surface of the panel and mixed quality lakes in the core (three-layer random board) or simply randomly distributing mixed uality flakes throughout (homogeneous random board). Emplacing the highest quality lakes on the panel surfaces improves bending strength and stiffness. Further control f processing steps--controlling closure rate and pressure to densify surfaces, using inimum resin to attain desired strength, selecting the proper proportion of surface lakes to core material--improves random three-layer structural flakeboard panels Ramaker and Lehmann 1976; Geimer and others 1975b).

Table 13.--*Selected performance goals for structural flakeboard*

Component	Thickness	MOE[1]	MOE[2]
	Inches	*Psi*	*Psi*
STATIC BENDING			
Floor	5/8	[3]800,000	4,000
16" c/c	3/4	475,000	3,000
Roofs	1/2	725,000	[3]4,500
24" c/c	5/8	375,000	3,000
Walls	5/16	500,000	2,500
16" c/c	3/8	300,000	2,200
RESIDUAL BENDING STRENGTH AFTER ACCELERATED AGING: 50 PERCENT OF INITIAL			
TENSILE STRENGTH PERPENDICULAR TO SURFACE (INTERNAL BOND)			
Strength--Dry		70 lb/in^2	
--After accelerated aging		35 lb/in^2	
DIMENSIONAL STABILITY (30 to 90 PERCENT RELATIVE HUMIDITY)			
Allowable linear expansion (in plane of panel)		0.25 percent	
Allowable thickness swelling		8 percent	
INTERLAMINAR SHEAR			
Strength		250 lb/in^2	
EDGEWISE SHEAR			
Strength		1,000 lb/in^2	

[1] Values are average values with a variability consideration.

[2] Values are near-minimum values.

[3] Values governing a single maximum performance panel.

Alining wood flakes or strands in one direction produces structural flakeboards o even higher strength and stiffness (Elmendorf 1965; Snodgrass and others 1973). To obtain adequate linear stability and strength in the nonalined direction, three-layer alined boards are suggested. The importance of this is reflected in figure 10, where expansion perpendicular to the alined direction can be very high unless restrained (Geimer and others 1975b). The cores consist of either random flakes or cross-alined flakes (Geimer, and others 1975a; Saunders and others 1975). (The alined panel paten (Elmendorf 1965) restricts commercial production of this panel type.) Typical surfac of random and alined boards are shown in figure 11.

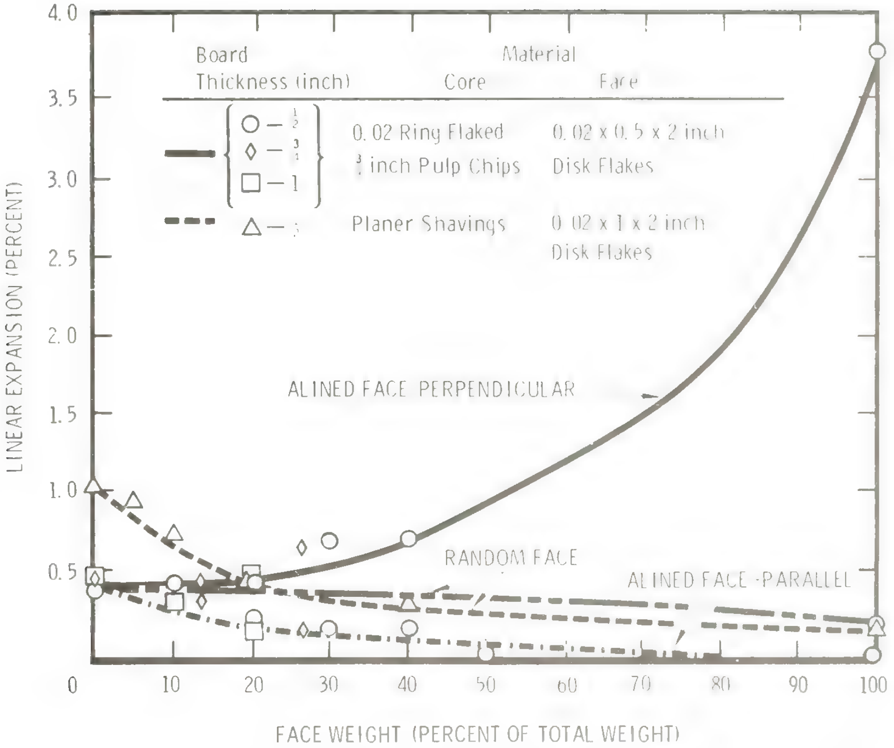


Figure 10.--Linear expansion of three-layer flakeboards after ovendry and vacuum pressure soak (Geimer and others 1975).

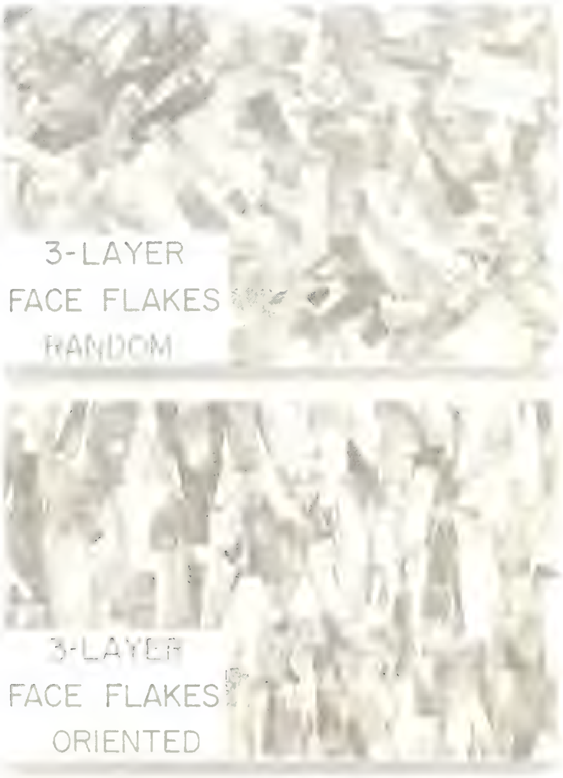


Figure 11.--Three-layer random surface and alined surface phenolic flakeboard constructions.

Table 14.--*Comparative properties of various structural flakeboard configurations from disk and ring flakes*

Flake type		Species[1]	Resin content	Dry specific gravity	Modulus of rupture	Modulus of elasticity	Internal bond	50-90 per relative hu Linear expansion
			Percent		*Lb/in*^{2}	*1,000 Lb/in*^{2}	*Lb/in*^{2}	*Percent*
		ALINED HOMOGENEOUS FLAKEBOARD						
Stands: 0.016 in by 1.5-3 in	--parallel	[2]VX	6	0.64	5,480	968	92	0.03
	--perpendicular				1,850	215		.40
Ring flakes: 0.016 in by 1.5-3 in from large chips	--parallel	VX	6	.67	6,110	777	113	.04
	--perpendicular				2,250	254		.26
Disk flakes: 0.020 in by 2 in by 0.05 in	--parallel	DF	5	.64	9,500	1,777	91	.00
	--perpendicular			.57	460	56		1.92
		3-LAYER ALINED FLAKEBOARD						
Alined face--cross-alined core strands: 0.016 in by 1.5-3 in	--parallel	VX	5-6	.75	5,500	899	125	.11
	--perpendicular				4,000	445		.11
Alined face--cross-alined core: Faces (30%): 0.02 by 2-in disk flakes	--parallel	DF	5	.65	6,580	1,398	112	.02
Core (70%): 1-in ring flakes from 1-in chips	--perpendicular			.63	3,110	412		.16
Alined face--random core: Faces (40%): 0.02 by 2-in disk flakes	--parallel	DF	5	.65	6,740	1,394	110	--
Core (60%): 3/4-in ring flakes from 3/4-in chips	--perpendicular			.65	2,050	240		--
Faces (30%): 0.02 by 2-in disk flakes	--parallel	DF	5	.72	6,620	1,247	86	.06
Core (70%): 0.02 by 2-in ring flakes from 2-in chips[2]	--perpendicular			.68	2,640	359		.28
	--parallel	LP	5	.70	7,750	1,299	130	.10
	--perpendicular			.68	3,560	348		.35
		3-LAYER RANDOM FLAKEBOARD						
Face flakes (30% bd wt): 0.02 by 2-in disk flakes plus 0.02 by 2-in ring flakes from 2-in chips (screened + 1/2-in) Core flakes (70 % bd wt): Above screened - 1/2-in		[2]DF	5	0.65	4,620	700	125	0.04
Face flakes (50% bd wt): 0.02 by 2 ring from 2-in chips Core flakes: Slivers		LP	4/2	.67	5,255	795	100	--
Face flakes (30% bd wt): 0.02 by 2 disk flakes Core flakes (30% bd wt): 0.02 by 2 ring flakes from 2-in chips		DF	5	.72	5,260	754	117	.10
		LP	5	.69	5,270	710	152	.15
		RANDOM HOMOGENEOUS FLAKEBOARD						
Ring flakes: 0.02 by 2-in from 2-in chips		DF	5	.67	4,340	608	105	.05
Ring flakes: 0.02 by 2-in from 2-in chips		DF	3	.63	4,015	705	65	--
Disk flakes: 0.02 by 2-in from 2-in chips		DF	5	.66	4,310	691	36	.07
Ring flakes: 0.02 by 2-in from 2-in chips		LP	3	.59	4,935	745	75	--
Disk flakes: 0.02 by 2-in from 2-in chips		LP	3	.59	5,185	770	130	--

[1] Chips, hand-cut: about 1-by 1-by 2-in

[2] Species code: DF, Douglas-fir from west of Cascades; LP, lodgepole pine, VX, variety of softwoods.

Property levels that are attainable in various board configurations at equivalent board densities are given in table 14. Generally, strengths above 5,500 psi and stiffnesses (MOE) in excess of 750,000 psi are easily obtained for experimental panels having alined flake configurations. One must provide cross-alinement or random orientation of flakes in panels, however, to limit linear expansion. Three-layer random or homogeneous flakeboards here have mean strengths in the range of 4,000 to 5,300 psi, and stiffnesses (MOE) in the range of 600,000 psi to 800,000 psi. Linear expansion is controlled by random orientation of the flakes. Internal bond levels for all panel configurations can be sufficiently high to assure meeting requirements. These results show that structural flakeboards can be prepared from sound wood residues that meet commercial standards and Forest Service specifications.

Furnish Requirements

Furnish for structural flakeboard (especially surfaces) must consist of longer flakes or stands than are normally found in particles in conventional particleboards. Surface flakes should average 2 inches in length and 0.020 inch in thickness (Lehmann 1974; Saunders and others 1975; Snodgrass and Saunders 1974). Furnish for the core should also consist mostly of long flakes to enhance linear stability.

Flakes may be produced from fingerlings or directly from roundwood (fig. 12). The flakes resulting from these two techniques differ in quality, but both may be employed alone or in combination with each other to provide high performance structural flakeboards. Disk flakes from fingerlings are of lower quality than disk flakes produced from roundwood, but by alining fingerling-derived ring flakes in the board, one may attain high performance levels (Snodgrass and Saunders 1974).

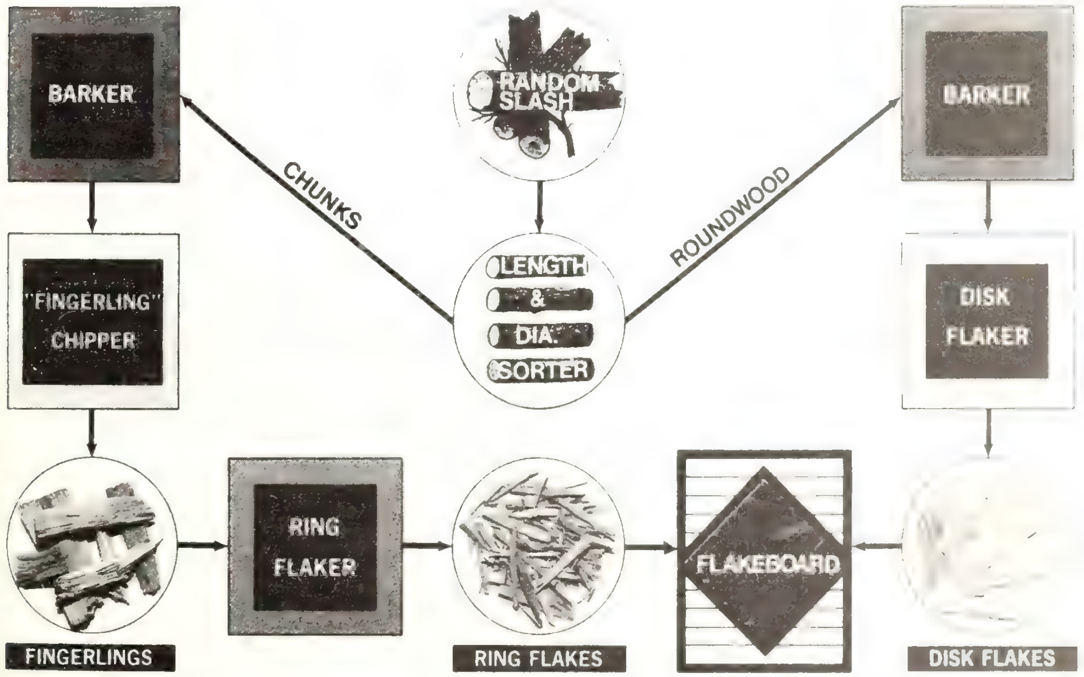


Figure 12.--Two parallel processing procedures for forest residue conversion into structural flakeboard.

Table 15.--*Comparative screen analyses of disk flakes (hammermilled) and ring flakes from unsound forest residue species. Ring flakes are derived from spiral or drum chipper fingerlings; disk flakes from split chunks. (Logs flaked when green except where noted.)*

Species	Percentage of material passing through 1/32-inch mesh screen	
	Ring flakes	Disk flakes (hammermilled)
	FROM SPIRAL CHIPPER FINGERLINGS	
Aspen	36	14
Paper birch	40	--
Western larch	24	14
Lodgepole pine	23	10
Lodgepole pine--dry logs	33	16
Douglas-fir	10	11
	FROM DRUM CHIPPER FINGERLINGS	
Douglas-fir (58 percent)-- Western hemlock (42 percent)	30	21
Douglas-fir	39	21

Fingerling Chips for Flakes

Many of the experimental panels produced for evaluation in table 14 included rin flakes generated from hand-cut fingerlings. In order to assess the quality of flakes derived from "chipper" fingerlings, experiments were conducted employing partially decayed forest residues (Heebink and Chern;[2] Heebink, and others, in press).

Included species were Douglas-fir, western hemlock, lodgepole pine, western larc aspen, and paper birch. Fingerlings from the spiral chipper and Arasmith drum chippe were flaked in a Pallmann ring flaker. Hand-cut chunks of similar material were disk flaked and then hammermilled. Homogeneous panels were prepared from each furnish retained on 1/32-inch mesh screen. The percentages of fines passing through a 1/32-i screen are given in table 15. Fines for the ring-flaked material were twice the hamm milled, disk-flaked material. Normally, for sound wood, the proportion of fines in hammermilled, disk-flaked material passing a 1/32-inch screen is about 3 to 5 percent The nearly 2 to 4 times the amount of fines generated here reflects the presence of barky or decayed wood and the influence of hammermilling.

Flaking decayed material produces proportionately smaller pieces than does flaki sound material, with the proportion of smaller flakes increasing with decreasing resi size. With sound wood (table 16), flake uniformity from disk and ring flakers is not different. About 93 percent of disk-cut flakes are retained on a >1/4-inch screen, while only 56 percent of ring flakes from hand-cut fingerlings are retained (Lehmann and Geimer 1974).

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[2] Heebink, B. G., and J. Chern. 1975. The "Spiral Chipper": evaluation of an initial reduction device to convert forest residues for structural particleboard. (Unpubl. FPL Off. Rep.)

Table 16.--*Comparative screen analyses of 0.20 inch thick disk flakes (nonhammermilled) and ring flakes produced from sound and decayed Douglas-fir forest residues (greater than 4 inches diameter) (Lehmann and Geimer [illegible])*

Screen mesh (inches)	Mean screen fraction			
	Ring flakes from hand-cut fingerlings		Disk flakes (nonhammermilled)	
	(Sound)	(Decayed)	(Sound)	(Decayed)
	Percent			
1/2	15.4	11.4	84.7	60.1
1/2 >1/4	40.6	29.6	8.6	22.4
1/4 >1/8	18.2	18.1	3.0	9.5
1/8 >1/16	12.7	18.5	2.0	5.4
1/16	13.2	22.4	1.7	2.6

Homogeneous random flakeboards were prepared employing 3 percent phenol-formaldehyde esin and 1 percent wax. The physical properties of the panels were evaluated and comared to assess the influence of flake type. Physical properties (before and after ccelerated aging) are given in table 17. Distinct reductions in strength are evident hen compared to similar panels produced from wholly sound wood (table 14), and again re attributable to lower wood quality used in panels shown in table 17. Levels for OR, MOE, and IB (internal bond) for many panels still exceed current Canadian and merican standards given in table 12.

Panels made from various kinds of flakes are compared in table 17. Ring-flake anels generally have reduced MOR and MOE levels compared to disk-flake panels, but IB s similar. Ring flaking hand-chipped fingerlings produces flakes that are inferior o those from disk flaking, but drum-chipped fingerlings induce a further reduction in ing flake quality (Heebink, and others, in press). Panel stiffness (MOE) again appears ost sensitive to the difference in quality of ring flakes from hand-cut fingerling nd drum-chipped fingerlings. No difference in linear expansion or thickness swell was etected between ring flakeboards and disk flakeboards.

To consistently obtain panels of maximum strength from ring flakes derived from orest residue, the flakes must be further separated during screening and the longest lakes placed in the panel surfaces.

Table 17.--*Mean strength properties for flakeboards of disk and ring flakes from forest residues containing decay.*

Species	Flake[1] type	Initial condition				After accelerated aging		
		Specific gravity[2]	Modulus of rupture[3]	Modulus of elasticity[3]	Internal bond	Modulus of rupture[3] Based on thickness prior to accelerated aging	Modulus of elasticity[3] Based on thickness prior to accelerated aging	Internal bond
Aspen	Disk	0.592	4,465	670	35	2,639	594	3
	Ring[4]	.576	2,682	443	35	1,834	368	3
Paper Birch	Disk	.589	2,156	426	38	1,332	243	3
	Ring[4]	.593	1,828	332	22	1,204	240	2
Western Larch	Disk	.585	2,375	335	45	1,332	192	14
	Ring[4]	.577	2,772	408	31	1,859	293	9
Douglas-fir	Disk	.608	4,119	543	74	2,880	438	25
	Ring[4]	.622	2,894	450	56	1,888	349	13
Douglas-fir	Disk	.595	2,744	503	53	1,776	342	21
	Ring[5]	.596	2,370	426	50	1,486	258	25
Douglas-fir(58%)	Disk	.595	3,339	487	46	2,992	505	28
Western hemlock (42%)	Ring[5]	.602	2,883	410	54	2,357	359	30
Lodgepole pine								
Dead	Disk	.578	4,034	594	32	2,908	485	19
	Ring[4]	.587	3,096	469	59	2,228	373	22
Green	Disk	.564	3,650	522	53	3,079	488	24
	Ring[4]	.590	3,173	486	73	2,635	463	10

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[1] Disk flakes: Logs reduced to 2-in-thick disks--disks were reduced to flakes on a disk flaker.

[2] Specific gravity based on ovendry weight and volume at 65% relative humidity.

[3] Corrected to a common mean specific gravity.

[4] Ring flakes: Logs reduced to fingerlings on "spiral chipper." Fingerlings reduced to flakes on a ring flaker

[5] Ring flakes: Logs reduced to fingerlings on "drum chipper." Fingerlings reduced to flakes on a ring flaker.

SUMMARY

Residue harvesting for structural flakeboard furnish should be increasingly economically attractive as markets in the Rocky Mountain area develop, structural flakeboard prices increase, and residue harvesting costs fall. Theoretically, a fingerling chipper working with one of five proposed harvesting systems could deliver fingerlings to the flakeboard mill for $25 to $33 per bone-dry ton for systems other than cable yarders.

The conversion of residue to fingerlings at the logging site for simplified handling and hauling appears to be attractive technically and economically. A modifie drum chipper and a spiral chipper can produce fingerlings in the woods or at the mill that can be further converted to ring flakes for alined-flake, or random-flake structural flakeboard that meets or exceeds commercial standards or Forest Service standards Experimental alined-flake flakeboard made from fingerling-derived flakes achieved mean strengths above 5,500 psi and stiffnesses (MOE) above 750,000 psi. Mean strengths of random-flake panels were above 4,000 psi and stiffnesses (MOE) above 600,000 psi. Because fingerling-derived ring flakes are inferior to disk flakes, high-strength structural flakeboards should employ disk flakes, or else the longest ring flakes should be positioned in the board surface.

A modified drum chipper with a 200 hp engine was estimated to produce 3/8-inch-thick fingerlings from large diameter residue at a rate of 50 tons per hour. Smaller residue (1-9 in) can be reduced to fingerlings in a spiral chipper at an estimated rate of 15 tons per hour (60 percent feed rate).

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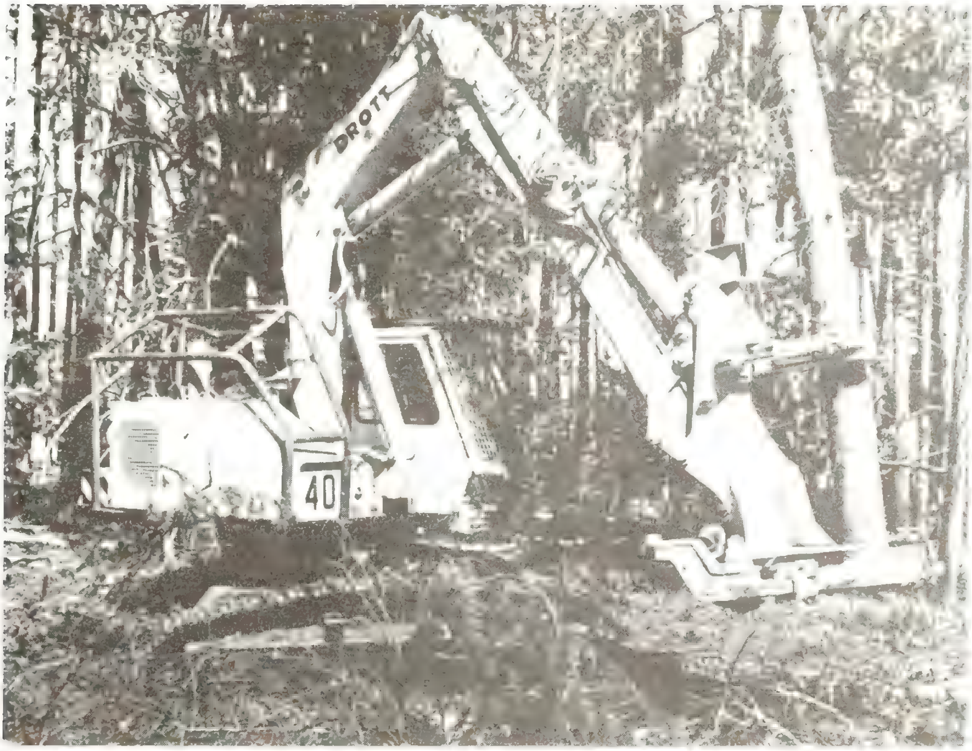
APPENDIX A

Special Equipment

The following section depicts (fig. 13-16) some of the special equipment involved in this study.



gure 13.--Drott Feller-Buncher, Model 40 LC. The tree is [illegible] shear, and controlled for bunching by the locking arm.

ure 14.--BM Volvo SM-880 Processor. The felled tree is grappled and returned to the olding arm. On the return travel of the boom for the next tree, the tree in the olding arm is prelimbed by the knives on the edge of the grapple arms; the tree is hen automatically transferred to the limber feed rolls and pulled through two raparound, belt-type knives. The tree is topped by a circular saw.

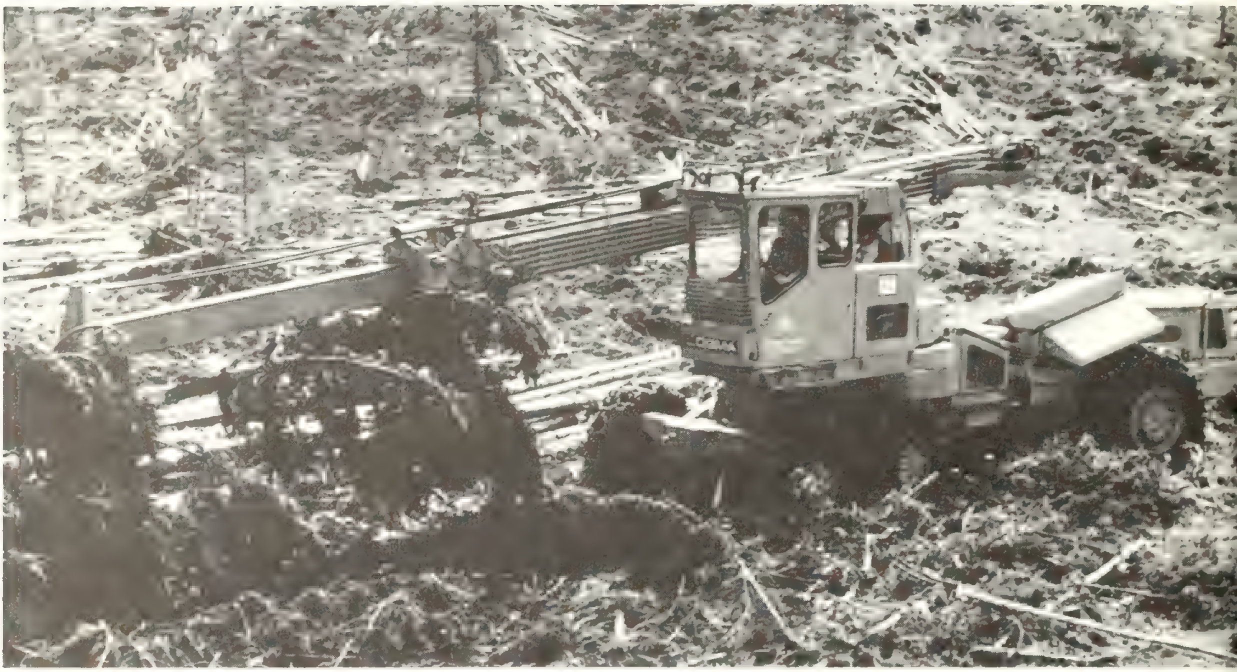


Figure 15.--Logma T-310 Limber-Buncher. Felled trees are grappled by the front set of limbing knives and drawn top first toward the machine. When the point of minimum to diameter is located under the rear set of knives, these grapple the tree and hold it while the top is sheared. With the rear set of knives holding the tree, the boom i extended and the front set of knives moves down the stem, removing the limbs.

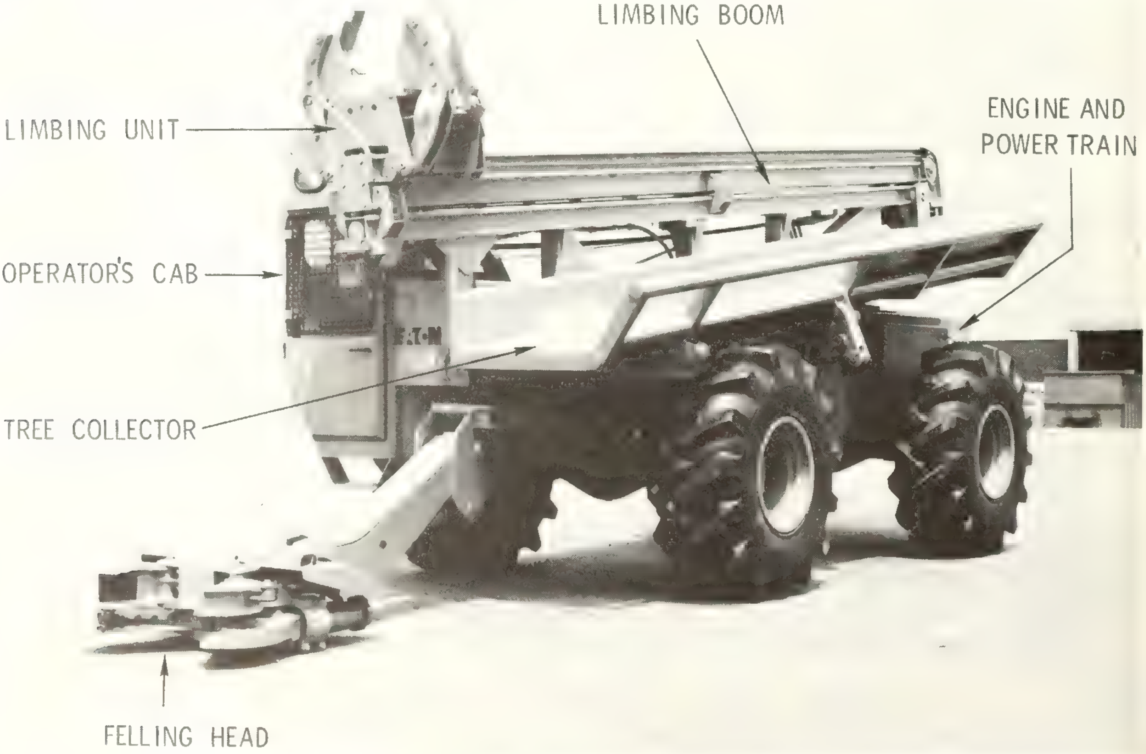


Figure 16.--Timberjack RW-30 tree-length harvester. Fells, limbs, bucks, and transports whole trees.

APPENDIX B

Operating Costs

When used to compare effectiveness of selected harvesting systems, cost must be omputed uniformly. Cost computations differ among owners. Some use straight-line epreciation and others may use double declining balance or sum of years digits. Also, ifferent allowances are made for repairs, maintenance, etc. The Equipment Data Sheet orm attached (fig. 17) was used for all equipment in this report to provide for more eaningful comparisons. Tables (18 and 19) show equipment, operator, and crew cost.

EQUIPMENT DATA SHEET

Specifications

Mfg. ______________________________

Model ______________________________

Engine ______________________________

General Specs. ______________________________

____

Standard Costs

Est. Life (N) ____________

Est. Use/Yr. ____________

Purchase Cost & Fgt. (I) ____________

Sal. Value (S) ____________

Fixed	**Ann.**
Dep. $\frac{I-S}{N}$	____________
Ave. Value of Invest. $\frac{I-S(N+1)}{2N} =$ ____________	
10% AVI for Int., Ins., Tx. and Storage	____________
Repairs and Maintenance (100% of Dep.)	____________
Total Ann. Cost	____________
Oper.	**Hour**
Fixed Costs + Hours of Use	____________
Fuel, Lub., etc.	____________
Total Cost/Hr.	____________

Figure 17.--Sample sheet for recording equipment data.

Table 18.--*Estimated equipment cost, 1975 prices.*

	Depreciation and Operation	Wages	Total
	--------------------	*Dollars*	--------------------
Chainsaw	1.28	5.50	6.78
Warner-Swasey[1] Log All	16.63	7.80	24.43
Drott LC-40 Feller-Buncher	16.63	7.80	24.83
Volvo SM-880	32.34	7.80	40.14
Logma T-310	20.85	7.80	28.65
RTS Grapple Timberjack 230D	9.48	7.20	16.68
Skagit GT-3	79.14	7.80	86.94
Cat 950 Front End Loader	20.73	7.80	29.53
Fingerlinger	12.08	7.20	19.28
Tractor-trailer	12.28	7.20	19.48
Loader LC-40	16.63	7.80	24.43
Harvester Timberjack RW-30	18.71	7.80	26.51

[1] No longer available.

Table 19.--*Estimated crew cost, 1975 wages.*

	Wages		
	Base	>20% B&PR[1]	Total
	----------	*Dollars*	----------
Heavy equipment operator	6.50	1.30	7.80
Light equipment operator	6.00	1.20	7.20
Choker setter	5.50	1.10	6.60
Knot Bumper	5.50	1.10	6.60
Rigger	5.50	1.10	6.60
Truck driver	6.00	1.20	7.20
Foreman	7.00	1.40	8.40

Skagit crew
1 Operator
1 Knot Bumper
2 Riggers (Trees are rigged ahead of logging sets.)
2 Choker Setters
6

[1] Benefits and payroll cost.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

- Billings, Montana
- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)

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NATIONAL FOREST SYSTEM
COOPERATIVE FORESTRY
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FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE

FOREST RESIDUES UTILIZATION
RESEARCH AND DEVELOPMENT PROGRAM

OW-COST HARVESTING SYSTEMS FOR NTENSIVE UTILIZATION IN SMALL-STEM ODGEPOLE PINE STANDS

John Host
Joyce Schlieter

A Forest Service
arch Paper INT-201

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LOW-COST HARVESTING SYSTEMS FOR INTENSIVE UTILIZATION IN SMALL-STEM LODGEPOLE PINE STANDS

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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RESEARCH SUMMARY

Three different skidding methods--small rubber-tired skidder, horse, small tracked tractor--were compared in an overmature lodgepole pine stand in Montana. Five comparable units were logged using two different utilization standards--loggers' choice and 2 1/2-inch top d.i.b. Skidding production, product volume removed per acre, and residue volume per acre are compared for each cutting unit. Skidding costs, in order of increasing costs were rubber-tired skidder, horse, and then farm tractor. On a capital investment basis, horse skidding is the most efficient.

INTRODUCTION

During the 1973 economic recession, Ravalli County, Montana, was an area of high nemployment. The Ravalli County Resource Conservation and Development Committee RC&D)--part of the Rural Area Development Program--located in Hamilton, began seeking eans for stimulating employment, particularly among farm and ranch workers chronically nemployed during the long winters.

One promising answer lay in expanding the logging of the large stands of lodgepole ine on the Bitterroot National Forest. The stands were underutilized at the time, and ndividual trees were of a size that could be skidded with equipment--also often idle n winter--found on many ranches and farms. Many ranchers who owned timber supplemented heir incomes by logging during the winter. Creating similar work for others seemed a ikely way to reduce unemployment.

The RC&D Committee enlisted the assistance of the staff of the Bitterroot National orest and the Intermountain Forest and Range Experiment Station's Forestry Sciences aboratory in Missoula. Two studies resulted from this cooperative effort. A study by enson and Strong[1] evaluated the acreage, volume, and product potential of lodgepole tands on the Bitterroot National Forest. The second study is the subject of this report

The study reported here had two objectives: (1) examine the feasibility of using nexpensive skidding equipment in a small-stem lodgepole pine stand in western Montana, nd (2) determine forest residues volumes (unused wood) resulting from different ground kidding methods and utilization standards. Preharvest volumes, volumes removed, residues left on the ground, and unusable material hauled from the site were determined or various utilization standards. The efficiency of skidding with a horse, small ractor, and small rubber-tired skidder were compared.

Benson and Strong[1] reported the volume and product potential of mature lodgepole ine stands on the Bitterroot National Forest. Mature lodgepole pine stands cover ,688 acres, of which only 44,147 acres are available for timber harvest. The cubic olume on these 44 thousand acres, 3 inches and larger in diameter, is segregated as ollows:

Standing green	91.3
Standing dead	26.7
Down	63.8
Total	181.8
Suitable for solid wood products	122.5
Suitable for fiber	36.1
Not usable	23.2
Total	181.8

---

[1] Benson, R. E., and R. A. Strong. Wood product potential in mature lodgepole ine stands, Bitterroot National Forest. USDA For. Serv. Res. Pap. INT-194, 16 p. termt. For. and Range Exp. Stn., Ogden, Utah.

This is further segregated into product groups:

Product	Million pieces			
	Green	Standing Dead	Down Dead	Total
Houselogs	1.4	0.3	0.4	2.1
Corral rails	6.0	1.4	1.1	8.5
Fenceposts	12.7	1.1	1.2	15.0

Pure stands of lodgepole pine are a major component of forest lands in the Rocky Mountains. The stands consist of numerous stems per acre, which are small diameter, 5 inches d.b.h. Frequently about half the per-acre volume is dead standing and down tre Table 1 points out the size classes, volumes, and sizes of these stands. Thirty-two billion board feet of sawtimber occur on 7.4 million acres. In general, a large porti of these stands are marginally operable because of high logging costs.

Because lodgepole pine comprises so much of the forests of western North America, there is growing interest in alternatives to the large, expensive tractors, skidders, and harvesters commonly used for harvesting timber. Close utilization of the stands, both as a means of extending wood supplies and as a means of disposing of the large vo and deadwood associated with overmature timber, is also of wide concern. Therefore th results of this study should be useful beyond the original purpose and scope of the wo

Table 1.--*Lodgepole pine stand statistics for Rocky Mountain area*

Diam. class	North. Idaho		South. Idaho		West. Montana		East. Montana		Wyoming		Colorado	
GROWING STOCK (MM FT^3)												
5.0-6.9	418.1		560.7		1,534.0		876.4		418.5		658.6	
7.0-8.9	479.4		561.5		1,620.0		1,076.0		435.4		454.3	
9.0-10.9	360.4		502.7		1,235.9		870.1		403.6		375.3	
Total	1,257.9		1,624.9		4,389.9		2,022.5		1,257.5		1,488.2	
NET SAWTIMBER VOLUME (MM BD. FT.) INT. 1/4-INCH RULE												
9.0-10.9	1,795.8		2,812.2		5,738.4		4,251.5		2,178.2		2,301.2	
11.0-12.9	1,307.0		1,924.1		3,221.2		2,944.6		1,472.3		1,844.4	
Total	3,102.8		4,736.3		8,959.6		7,196.1		3,650.5		4,145.6	
AREA IN M ACRES												
	NF	PVT	NF	PVT	NF	PVT	NF	PVT	NF	PVT	NF	PVT
Pole	438.4	64.7	213.3	18.5	1,145.6	328.2	645.4	148.5	460.9	31.7	237.2	267.3
Saw.	115.7	30.9	703.4	22.2	615.2	41.0	803.3	116.8	418.5	57.1	359.1	71.9
Total	554.1	95.6	916.7	40.7	1,760.8	369.2	1,448.7	265.3	879.4	88.8	596.3	339.2

SOURCE: Green, A. W., and T. S. Setzer. 1974. The Rocky Mountain timber situation, 1970. USDA For. Serv. Res. Bull. INT-10. Intermt. For. and Range Exp. Stn., Ogden, Utah.

STUDY AREA DESCRIPTION

The study area consists of five cutting units located on the Bitterroot National orest about 20 miles from Hamilton, Montana (fig. 1). A well-traveled road formed the ower boundary of the cutting units. (This road is also the upper boundary of a esignated roadless area.)

The study area was selected for uniformity of terrain and timber stand. Elevations anged from 6,700 to 7,040 feet above sea level. The logged slopes ranged between 20 nd 45 percent. All five units were situated in a stagnant, overmature 120-year-old odgepole pine stand. (The cover photo of this report shows stand condition prior to utting.) The silvicultural prescription was to clearcut and burn the slash, if nec- essary. Individual cutting units ranged from 1.13 to 1.65 acres.

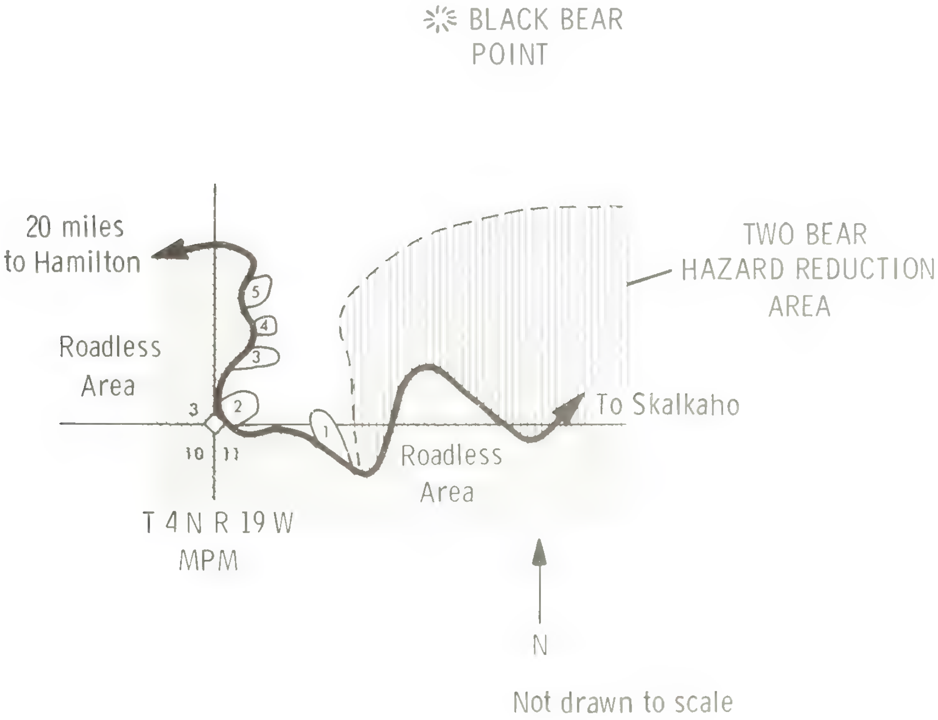

Figure 1.--Study area location.

PREHARVEST INVENTORY

Inventory data are presented for each unit in four stages: preharvest, harvest, postharvest and final product recovery. Average tree sizes and volumes for the diffe units were similar (table 2). D.b.h. ranged from 5.5 to 9.5 inches for all trees in t five units. The mean tree volume was 6.0 to 8.3 ft^3 for green trees and 2.7 to 5.2 ft for dead trees. The cubic volume per acre for the various units varied between 4,104 and 5,588 ft^3. Preharvest inventory provided a baseline for measuring residue cleanu efficiency.

Procedures described by Brown (1974)[2] were used in preharvest and postharvest inventories of downed material. This procedure consists of measuring down material along a random line and converting measurements to cubic volumes.

Table 2.--*Preharvest inventory*

Unit No.	1	2	3	4	5	Total
Size (acre)	1.13	1.57	1.54	1.65	1.50	7.39
			STAND VOLUME (FT^3)1/			
Standing	1,596	2,599	3,004	4,877	3,598	15,674
Down	4,669	3,844	5,601	4,017	2,949	21,080
Total	6,265	6,443	8,605	8,894	6,547	36,754
Vol per acre	5,544	4,104	5,588	5,390	4,365	
			MEAN TREE VOLUME (FT^3)2/			
Green	8.3	7.1	7.3	6.0	6.5	
Dead	5.2	4.8	4.1	2.7	4.1	
			TREE D.B.H. (INCHES)			
Mean	7.1	6.8	7.0	6.4	6.4	
Range	5.5-9.5	5.6-7.7	5.6-8.8	5.7-7.2	5.9-7.4	

1/ Stand gross volume to 2 1/2 inch top d.i.b.

2/ Whole tree gross volume to 2 1/2 inch top d.i.b.

---

[2] Brown, J. K. 1974. Handbook for inventorying downed woody material. USDA Fo Serv. Gen. Tech. Rep. INT-16, 24 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

HARVESTING ACTIVITY

Production was determined for three different ground skidding systems in five ogging units skidded as follows:

Logging Unit	*Skidding System*
1	Rubber-tired skidder
2	Small, tracked tractor
3	Horse, Rubber-tired skidder
4	Horse
5	Rubber-tired skidder

Unit 3 was originally assigned to be horse skidded. Excessive steepness prevented orse skidding the entire unit; hence, the rubber-tired skidder was used on part of hat unit.

The sale originally specified a 2 1/2-inch minimum top diameter and green material nly. This was later changed to "logger's choice," which meant the purchaser had the ption of taking or leaving any of the dead material. Green tree lengths were utilized p to the legal hauling length limit of 50 feet and some lengths exceeded this limit. here was no diameter limit. For dead material, the minimum top diameter was 2 1/2 nches and the trees had to be free of rot. Table 3 summarizes the operating conditions or each unit.

Table 3.--*Operating constraints and practices for each logged unit*

Unit	Utilization standard	Prelog activity	Skidding constraints
1	Full tree, green and sound dead	Stumps to ground level; direct fall uphill	None
2	Full tree, green and sound dead	Stumps to ground level; direct fall uphill	None
3	Full tree, green and sound dead	Stumps to ground level; direct fall uphill	Steep portion required diagonal slope skidding
4	2 1/2-inch top d.i.b.; green material	Stump height; less than 12 inches	Skidding followed prepared skid trails
5	2 1/2-inch top d.i.b.; green material. (Some dead removed for roadside decking.)	Stumps to ground level; direct fall uphill	None

The usual procedure for skidder and tractor methods was to skid at least a full truckload, then load the material and haul it out on the way home at the end of the shift. Hence, the workday consisted of driving the truck to work, skidding until 1 or 2 p.m., and loading and hauling the material to a sawmill or post and pole plant. Normal procedure was to start at a fixed time, 7:30 a.m., but skidding time ended when the operator assumed he had enough time and material to load his truck by 4:30 p.m. Consequently, skidding time ended from 1:05 to 3:30 p.m., with an average quitting time, 2:03 p.m. With a 60-minute lunch period, this represents a normal skidding day of 5 hours and 33 minutes, with 2 hours and 27 minutes for loading.

SKIDDING PRACTICES

Rubber-Tired Skidder

The rubber-tired skidder was a Garrett Tree Farmer Model 15, with a 60-horsepower engine. Total operating costs, itemized in the appendix, amounted to $10.18 per cunit (100 ft^3) skidded.

Felling was done to favor the skidding operation. All trees were felled uphill, with stumps being cut as close as possible to the groundline to allow the skidder to travel anyplace on the unit. This extra effort facilitated the skidding operation.

On unit 5, boles were bucked at 2 1/2-inch diameter when felled. Unit 1 was full-tree skidded except where the trees obviously exceeded legal hauling length. Hooking, skidding, and unhooking were all done by the skidder operator. Chokers consisted of hi tensile chains with slider hooks. This permitted winding around the pieces so the pieces would be straightened out when bunching the turn together. Hence, it was possib to handle a large number of pieces per turn.

The lower boundary of all the units was a well-traveled road--especially so during hunting season. This road was used as a landing for all five units. The sale contract required the purchaser to keep the road open for through traffic. Unit 5 was skidded during hunting season. This unique situation necessitated that time spent on the landing be considered as a separate production element so total round-trip time would not b affected.

Horse Skidding

Only the lower third of unit 3 was horse skidded because the upper two-thirds of the unit was too steep. The logs tended to slide into the horses on a straight downhi pull and the units were too narrow to efficiently zigzag skid trails. Unit 3 was finished with the rubber-tired skidder after a trial with the farm tractor. Unit 4 was completely horse skidded.

On unit 3, trees were cut at the groundline and felled uphill to simplify the skidding operation. Felling on unit 4 was done with no consideration for horse skid trails. Consequently, as skidding proceeded into unit 4, skid trails had to be cleaned out and high stumps cut at groundline to prevent stump hangups.

Because of the small timber, a single horse sufficed for skidding. A log chain with a slip hook at one end for the log and a grab hook at the other end attached to the single tree was used to hook the logs. The landings for these units (3 and 4) wer situated so as to minimize the necessity of clearing the road for traffic.

Although only one horse at a time was used for skidding, the operators had a elief horse, and horses were changed approximately every 2 hours. Generally, on a ross time basis, skidding was carried on for about 6 hours per day. One operator orked his horses from 7:00 a.m. until 3:00 p.m., with two half-hour rest periods and one-hour lunch break. The other operator worked 8:30 a.m. until around 5:00 p.m., ith variable rest and lunch breaks. On an 8-hour workday basis, horse skidding cost 77.52 per day or $12.48 per cunit.

Tractor Skidding

The tree felling operation for the tractor consisted of cutting the trees at ground evel and pushing them uphill. Bucking that was necessary to meet legal load length as done on the truck rather than on the logging unit. (The hooking, bunching, skidding, nhooking, and landing operations were similar to the rubber-tired skidder operations.)

The tractor was a 25 hp John Deere Model 420, which is a fairly common size for ight ranch work in the area. The operator was the same person who operated the rubber-ired skidder. Thus, it is reasonable to assume that the nonoperating functions would e closely comparable for both methods. Also, the differences in travel times should e free of operator performance differences. At a cost of $79.26 per day, the track kidding cost $15.70 per cunit.

STUDY RESULTS

Inventory of wood on the units prior to harvesting, measurement of material reoved, and reinventory of the units after harvesting provide a basis for describing tilization, product recovery, and residue remaining.

Harvesting Statistics

Harvest volume is the total cubic volume skidded to the landing. Except for pproximately 126 ft^3 of fuelwood left in a cold deck, all the material skidded to the anding was loaded out and hauled to a sawmill or post and pole plant. This material as classified as green or as dead. Table 4 shows the material removed from each unit, ad material remaining as residue on the site. Figure 2 is a distant view of unit 4 ight) and unit 5. Figures 3 and 4 show closeups of residues on units 4 and 5, espectively.

Volumes of net usable material were determined from a computer program designed o calculate products and volumes from each piece loaded out. Three inspections at e log yard confirmed program reliability.

"Yard residue" refers to the amount of cull, or nonutilized material, hauled to e mill or post yard. Material removed from units 1 and 2 contained a large proportion unutilizable material, according to the program. Much of this "yard residue" was sposed of as free firewood.

The residue removal ratio compares the volume of yard residue to total (logging us yard) residues. A high ratio suggests a clean logging job. That is, logging esidues have been carried to the yard. The difference is illustrated by the high oduct/residue ratio of 6.56 for unit 5.

Table 4.--*Volume removed and volume remaining after logging*

	1	2	3	4	5	Total
Area (acre)	1.13	1.57	1.54	1.65	1.50	7.39
			HARVEST[1] INVENTORY IN FT^3			
Live	4,678	2,381	4,851	858	2,390	
Dead	2,393	1,217	1,103	1,121	891	
Total	7,071	3,598	4,954	1,979	3,281	20,883
Product	3,006	1,588	3,073	1,694	2,847	12,208
Yard residue[2]	4,065	2,010	1,881	285[3]	434	8,675
Product/yard residue ratio	.74	.79	1.63	5.94	6.56	1.41
Average piece volume(ft^3)	4.73	4.51	4.53	5.76	4.89	
			POSTHARVEST INVENTORY IN FT^3			
Logging residue	1,425	1,732	3,539	2,454	963[4]	10,113
volume/acre-ft[3]	1,261	1,103	1,102	1,487	642	1,315

---

[1] Harvest volumes are based on total volume of individual pieces loaded onto the truck. Product volume is based on total volume of individual products derived from the material loaded onto the truck.

[2] Yard residue = total harvest volume less product volume.

[3] Material from unit 4 was to be delivered to a sawmill, while the material from the other four units went to a post and pole plant. Material from units 1, 2, and 3 were processed to highest value use.

[4] Does not include a roadside deck of dead material containing approximately 126 ft^3. This material was left as fuelwood. The next summer practically all this material had been cut up and hauled away.

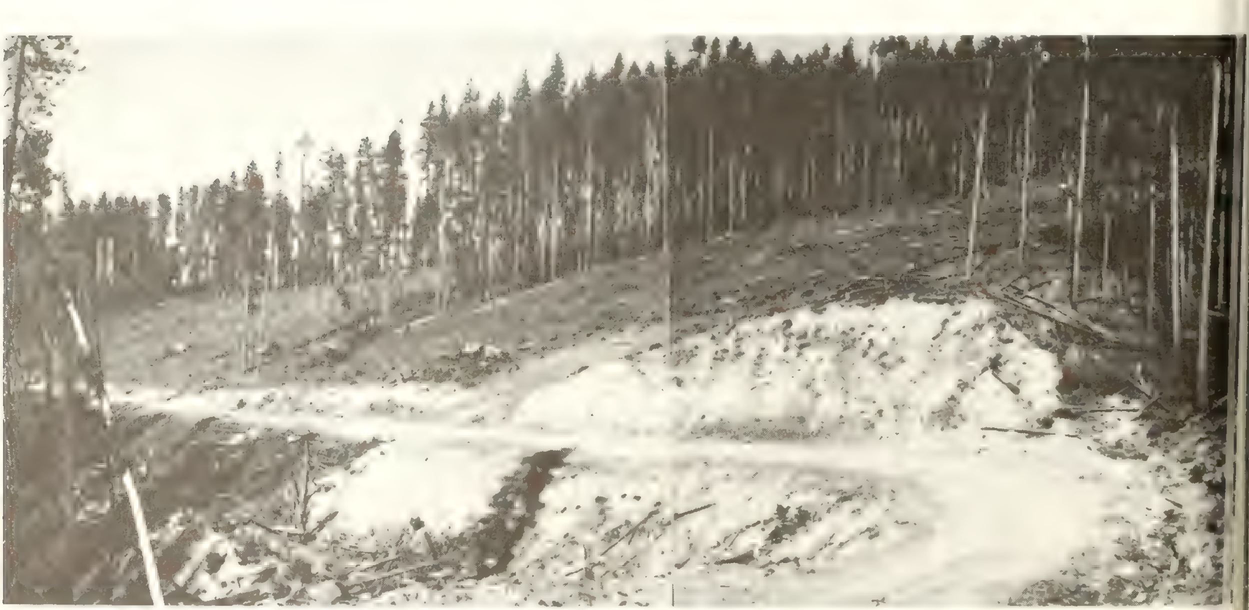

Figure 2.--Units 4 (right) and 5 after harvesting.

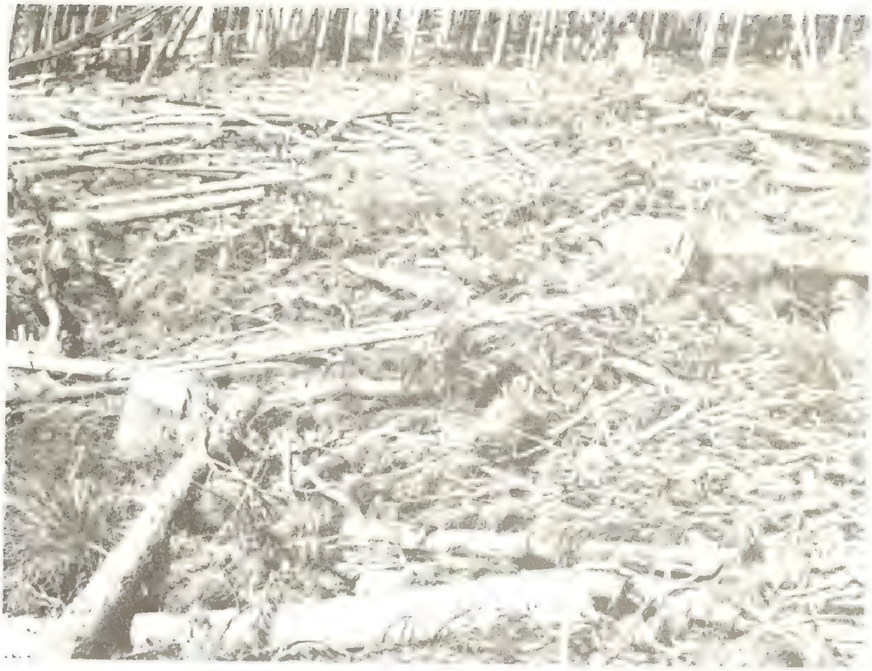

Figure 3.--Postharvest residues on unit 4.

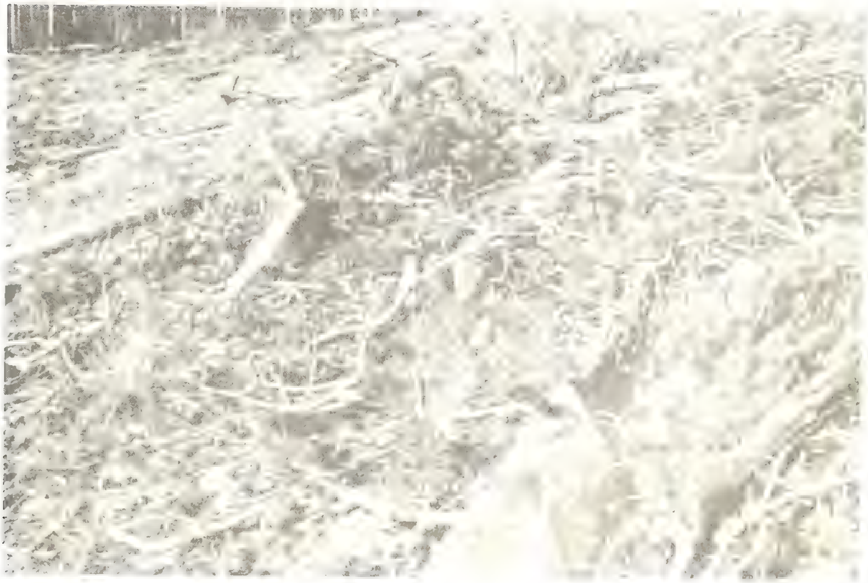

Figure 4.--Postharvest residues on unit 5.

PRODUCT RECOVERY

Up to this point material utilized has been considered as a volume of usable wood. The following section considers the kinds of products that can be derived from this volume and type of wood.

Utilization Standards

This experimental sale originally specified utilization to a 2 1/2-inch minimum top diameter for green material. The specification was later changed to "logger's choice," which meant that the purchaser had the option of taking or leaving any of the dead material on the sale. For green material, whole-tree lengths were utilized up to the legal hauling length limit of 50 feet, with no minimum diameter. Dead trees had to be free of rot. Consequently, material that was on the ground prior to the falling operation was not removed.

The minimum piece length skidded was long enough to contain 2 or more products--2 houselogs, or 1 houselog and 1 studlog, etc. The primary length constraint was legal hauling length. Another consideration was the amount of rot in dead material.

Product specifications were as follows:

Product		*Min. small-end diameter* (Inches)	*Min. length* (Feet)
Sawlog		12	8
Studlog		6	8
Houselog		8	12
Fencepost	1	6	7
	2	5	6
	3	4	6
	4	3	6
	5	2	5

Product recovery, in number of pieces and cubic volumes, is shown in table 5. Recovery is computerized, based on the length and diameters of the material loaded fro each unit. Recovery is optimum because material is allocated to its most valuable end use. A sample estimate of the products at the plant site showed that the actual multiproduct recovery was as good as the programed recovery because of close tolerances in cutting out the products. For instance, some houselogs were actually a scant 8 inches in diameter and some 7-foot posts were 5 3/4 inches in diameter. It wa not possible to get an accurate yard tally because products were mixed in the yard.

Recovery of larger, more valuable material was quite high--31 percent of total recovered volume--for the tree sizes involved. On the other hand, the large proportion of posts represents product recovery beyond what might be expected by a single product studlog operation. This table shows that the so-called unusable tops do have some use.

Table 5. [illegible]

Unit	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Product							
Saw log-number	1	3	[illegible]	[illegible]		11	
Houselog-number	66	[illegible]	81	[illegible]	64	[illegible]	
Studlog-number	350	154	[illegible]	[illegible]		[illegible]	
Number pieces, total	417	193	439	[illegible]	323	1,601	
Cubic volume, total	976	400	[illegible]	[illegible]	1,015	[illegible]	
Fencepost							
Class-1	34	26	14	5	7		
2	329	270	472	257	[illegible]		
3	680	395	643	[illegible]	404		
4	613	386	635	[illegible]	432		
5	632	[illegible]	558	[illegible]	[illegible]		
Number pieces	2,488	1,436	2,322	1,252	1,553	[illegible],041	
Cubic volume	2,030	1,188	2,141	1,198	1,832	[illegible]	69%
Total pieces-product	2,905	1,629	2,661	1,481	1,876	[illegible]	
Total volume-product	3,006	1,588	3,073	1,694	2,847	12,208	
Pieces hauled	1,495	797	1,313	326	671	4,602	

Product specifications:

Saw log = 12-inch diameter · 8-foot length
Studlog = 6-inch diameter · 8-foot length
Houselog = 8-inch diameter 12-foot length
Fencepost 1 = 6-inch diameter 7-foot length
Fencepost 2 = 5-inch diameter 6-foot length
Fencepost 3 = 4-inch diameter 6-foot length
Fencepost 4 = 3-inch diameter · 6-foot length
Fencepost 5 = 2-inch diameter 5-foot length

The number of pieces hauled from the woods was less than half (43 percent) the umber of pieces finally derived from the material. This indicates how whole-tree lgging can reduce handling costs. Whole-tree logging also permits efficient product coices, which improves product values. Conversely, multiproduct utilization permits fll-tree logging, which reduces handling costs up to the product-bucking operation.

Residue Utilization Analysis

As defined earlier, residues are any unused wood materials. Harvest residues are sash. Yard residues are the residues left in the post yard. In the fall of 1973, post dmand was high. The incremental cost of handling yard residues might be considered a the additional cost incurred to assure maximum material recovery.

The total product/yard residue ratio indicates the proportion of all the material huled from the logging site that was usable. Conversely, the reciprocal of the ratio idicates the proportion of the hauled material that was yard residue. Total logging rsidue was only slightly higher than the total yard residue. This indicates that about 46 percent of all the residues generated on all five units was hauled away.

HARVESTING PRODUCTION ANALYSIS

Regression Analysis

Harvesting production was analyzed using regression analysis of important variables Time was the dependent variable. The different independent variables were number of pieces per turn, skidding distance, and volume per turn. A prediction equation is of the form

$$Y = b_o + b_1X$$

Where b_o is the intercept and b_1 is the slope of the line. Table 6 shows the regressio coefficients, b_o and b_1, R^2 and the F-statistic for all three skidding methods. R^2 indicates how important the specific independent variable is in explaining the variation of the equation. The F-statistic was used to test the significance of the regression.

Cases where the regression is not significant indicate that the data do not fit a straight line, or that there is no relationship between the variables compared in that instance. Scatterplots of the data were examined in these nonsignificant cases. The independent variable did not appear to affect the dependent variable, time.

Table 6 shows that distance has very little effect on travel time in and out. In this study the range of distances was too limited. However, it does appear that distan affects travel time more for the skidder and tractor than for the horse. Number of pieces per turn had more effect on hook time for the skidder and tractor than for the horse. (This is partially explained by the fact that the horse crew had a helper getting the next drag ready for hooking.) Roundtrip time is more dependent on volume per turn for the skidder and tractor than for horse skidding.

Table 6.--*Prediction equation regression coefficients, R^2, and F for skidding production*

Dep. var. Y	X	Skidder				Horse				Tractor			
		b_o	b_1	R^2	F	b_o	b_1	R^2	F	b_o	b_1	R^2	F
Time out	Dist.	1.38	0.006	0.22	43.1*	1.34	0.001	0.05	4.5*	1.63	0.006	0.21	18.5*
Time in	Dist.	1.06	.006	.22	44.8*	.78	.006	.17	16.8*	1.24	.008	.20	17.0*
Time in	NP	2.24	.02	.005	.81	1.55	.07	.02	2.0	2.42	.08	.04	3.1
Hook time	NP	1.05	.54	.35	83.9*	1.50	.14	.18	17.7*	.31	.62	.72	175.2*
Unhook time	NP	1.12	.06	.03	4.8*	.27	.04	.11	9.4*	.58	.15	.28	26.0*
RT time	NP	10.8	.60	.16	30.6*	7.46	.23	.08	7.4*	6.63	1.3	.58	95.0*
RT time	vol/turn	11.5	.12	.15	27.8*	7.63	.04	.07	6.2*	7.11	.28	.56	85.3*

$Y = b_o + b_1X$

* indicates significance at 0.05 probability level

RT = round trip

NP = number of pieces

Multiple regressions were also run on the data, with round trip time as the dependent variable and various combinations of distance, number of pieces, volume per piece and volume per turn as the independent variables. The equations are of the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$$

The results are summarized in table 7. All regressions are significant at the 0.05 probability level.

Table 7.--*Multiple regression intercepts, coefficients, R^2 and F-statistic for skidding production*[1/]

b_0	b_1	b_2	b_3	b_4	R^2	F
ntercept	*Distance*	*No. Pcs*	*Pc Vol*	*Turn Vol*		
		SKIDDER				
4.08	0.02	0.61			0.32	54.0*
13.85	.02	.45	4.33		.40	49.3*
3.82	.02			0.14	.37	66.2*
		HORSE				
4.19	.02	.16			.29	20.1*
2.57	.02	.14	.33		.31	14.4*
4.03	.02			.04	.30	21.6*
		TRACTOR				
.41	.03	1.2			.70	78.8*
31.97	.03	1.2	-6.84		.71	54.9*
.53	.03			.26	.68	72.8*

[1/] Subscripts refer to following variables:
0 - intercept
1 - distance
2 = number of pieces per turn
3 = volume per piece
4 = volume per turn

* Indicates significance at 0.05 probability level

Using R^2 as a measure of reliability, table 7 suggests:

1. multiple regression does not improve the reliability of prediction equations;

2. although the reliability of the prediction equation for the rubber-tired idder and horse is quite low, it is high for the tractor skidder.

Table 8.--*Average times for logging tasks and character of average turn (TOT = total operating time) (RTT = Round trip time)*

	Skidding Method								
	Skidder			Horse			Tractor		
Element (task)	Minutes	% of TOT	% of RTT	Minutes	% of TOT	% of RTT	Minutes	% of TOT	% of RTT
Time out	2.8	14.0	15.8	1.5	18.1	18.1	3.3	12.4	14.7
Time in	2.5	12.5	14.1	1.8	21.7	21.7	3.4	12.8	15.1
Hook time	7.2	36.1	40.7	2.0	24.1	24.1	7.8	29.3	34.7
Bunch time	3.3	16.5	18.6	2.6	31.3	31.3	5.6	21.1	24.9
Unhook time	1.9	9.5	10.7	.4	4.8	4.8	2.4	9.0	10.7
Round-trip time	17.7	--		8.3	--		22.5	--	
Landing time	2.0	10.0		.0	.0		3.7	13.9	
Total Operating time	20.0			8.3			26.6		
Turn character									
No pc/turn		11.5			3.7			12.1	
Dist. (ft)		254.0			164.0			260.0	
Slope (%)		19.0			22.0			21.0	
Production									
Pc/8 h		168.0			125.0			112.0	
Vol/8h-ft^3		795.0			621.0			505.0	

Table 8 presents the average times for separate logging tasks and character of th average turn for different skidding methods. The effect of labor can be estimated by comparing the labor-intensive tasks--hook time and unhook time. Because bunching time is part of the hooking process for horse skidding, it is necessary to include bunching for the skidder and tractor skidding for comparative purposes. The percent of round trip time, which excludes landing time, was:

	Skidder	*Horse*	*Tractor*
	--------*(Percent)*--------		
Hook time	40.7	24.1	34.7
Bunch time	18.6	31.3	24.9
Unhook time	10.7	4.8	10.7
Total	70.0	60.2	70.3

The total percentage of round trip time was as expected. That is, horse skiddin ought to be lower than for the other skidding methods. The average number of pieces turn explains this--3.7 for pieces horse skidding, 11.5 pieces for the skidder, and 12.1 pieces for the tractor.

Table 9 shows a production comparison on an 8-hour shift basis. Because the shi hours were not the same for all three skidding methods, the gross shift production is presented on an assumed 8-hour shift. Because horse skidding had no landing time, th will tend to distort horse skidding production time. This distortion is eliminated b including the column headed "% of # RTT", which is percent of round trip time, excluc landing time, for all three skidding methods.

Table 9.--*Production* [illegible]

Item	Skidding Method Skidder	 Horse	 Tractor
Residue vol./acre-ft^3	908	1,487	,103
Product vol./acre-ft^3	1,125	726	757
Post material-% total product vol.	66	71	75
Man-days/acre	6.8	9.7	6.9
% of skidder	100	143	101
No. pcs/8 h day	168	125	112
% of skidder	100	74	67
Vol./8 h day-Cunit	7.95	6.21	5.05
% of skidder	100	78	64
Skidding Cost/cunit-$	10.18	12.48	15.70
% of skidder	100	123	154

CONCLUSIONS

Residue Reduction

Table 9 summarizes the study data. Although the top of table 9 is related to utilization standards rather than skidding methods, it shows the residue volumes that resulted. Assuming that the post material would probably be logging slash on a conventional harvest, at least 66 percent of the total products removed from the area would have been slash. Or, through increased utilization the logging residues were reduced to one-third or one-half times what might have been left. Logging residues have been reduced further because of the treetops hauled from the logging site, much of which became yard residues. Tables 2 and 4 show:

Initial Volume		36,754 (table 2)
Standing	15,674	
Down	21,080	
Volume removed		20,883 (table 4)
Products	12,208	
Yard residue	8,675	

The additional 8,675 ft^3 of material removed that was unsuited for solid wood products represents 24 percent of the total initial volume or 42 percent of the total material removed. The value of this material depends upon local markets. At the time of the study the post market was very good. Some of the material classed as unusable was used for small, electric-wire fenceposts and small, class 5 fenceposts. A large part of the material was disposed of as free firewood. During periods of tight chip supplies, the material could be chipped.

Effect of Skidding Variables

Based on the b_1 coefficient listed in table 6, the following observations can be stated:

1. The rubber-tired skidder was underutilized. That is, the b_1 coefficient is t same for both directions of travel, emptied out and loaded in. Also, the number of pi per turn had less effect on travel time in for the skidder than for either of the othe two skidding methods. The average number of pieces per turn for the skidder was 3 tim more than for the horse and almost equal to the number for tractor skidding.

2. The horse was utilized well because of the difference in b_1 coefficient for time out (0.1 min) versus time in (0.6 min), per hundred feet of skidding distance.

There was no appreciable difference for steepness of skidding, except the upper portio of unit 3, to permit any comparison of grade effect on skid time.

Capital Investment and Production Efficiency

An important part of this study was to determine the capital investment levels to achieve different production levels. As it turned out, there were only two different levels of investment. Production levels, as measured by number of pieces skidded per day or cubic volume skidded per day, varied considerably. Table 10 is derived from table 8 and cost determinations in the appendix.

Table 10 shows:

For horse skidding,
60 percent of investment for skidder will produce
74 percent as many pieces per day or
78 percent of the daily volume for the skidder.

For the small farm tractor,
60 percent of investment for skidder will produce
67 percent as many pieces per day, or
64 percent of the daily volume for the skidder.

Table 10.--*Production and capital investment comparisons*

	Method		
	Skidder	Horse	Tractor
No. pieces/day	168	125	112
% of skidder	100	74	67
Cubic feet/day	795	621	505
% of skidder	100	78	64
Investment (dollars)	2,500	1,500	1,500
% of skidder	100	60	60

It is apparent that, based on this case study, the capital invested for skidding horses is more efficient than either of the other two skidding methods. Also, on a cost per cubic volume skidded, the horse is more efficient than the farm tractor. Although it is beyond the scope of this study, alternative uses for the tractor could very well make it the better choice.

Land Management Implications

1. Logging slash can be reduced considerably through logging procedures and utilization standards that require removal of small roundwood products. In fact, the slash disposal costs were minimal. Pile-and-burn along the road was the only slash abatement work done.

2. For processing plants where this material can be used for pulp chips and fuel, the yard residues can be utilized by machine-debarking the chips. Further studies on utilization economics of this material are needed to more fully evaluate the impact on land management possibilities.

3. An economical system for operating in this type of stand--stagnant growing stock size--would certainly help to get similar stands under management. The Rocky Mountain area has considerable acreage in this condition.

Product Recovered

The product recovered is greatly dependent upon the piece diameter and length. Bucking out rot reduced product options and values.

Slash volume studies in Engelmann spruce stands show a 50 percent product recovery in saw log operations. This is in higher value material with normal utilization standards. Hence, it is apparent that a recovery of 12,208 ft^3, or 33 percent of total initial volume, is a reasonably good recovery in these stands perceived to be marginally inoperable. When considering the yard residues, the total volume removed, 20,883 ft^3, amounts to 57 percent of the initial volume.

APPENDIX

Operating Costs

The appendix shows how operating costs were determined. The machine costs have en based on values of used machines, while the horses were considered as young horses.

The machines are smaller than might normally be available. Also, these machines, ile doing the job efficiently, were well past their normally depreciable life span. eir replacement cost would certainly be much higher than the listed purchase price. t, it is unlikely that a new machine would we used on this type of logging chance. nce, the listed purchase price relates to the market values of the machines when the udy was undertaken.

The horses were priced at their current age value. It is assumed that this sort work would be limited to mature, vigorous animals that bring high prices.

SKIDDER OPERATING COST

Model 15 Garrett Tree Farmer (1965)

Purchase Price $2,500

Useful Life 5 years

Depreciation $500/yr with zero resale. $55.56/month @ 9 month/yr $2.65/day @ 21 days/month	$2.65
Interest, Insurance, and Tax = 10% AAI $1,250 x 10% = $125.00 = 70¢/day	.70
Tires = $500/year = 265/day	2.65
Maintenance & Repair = $550/year = $2.91/day	2.91
Operator @ 8.00/hour = $72.00/day	72.00
Total Daily Cost	$80.91

HORSE OPERATING COST

Purchase price $750/horse, $1,500.00

Useful Life 4 years

Depreciation = $375/yr = $1.98/day		$1.98
Upkeep 1 horse		
426/6 month working	$606/yr	
180/6 month nonwork	$3.21/day	6.42
Shoes = $96/yr - 51¢/day		1.02
Harness = $250/yr = $1.32/day		2.64
Vet Service = $150/yr or $200/2 horses		1.06
Tax, Interest, Insurance = AAI x 10%		
$740 x 10% = 40¢		.40
Teamster $8.00/hr		64.00
Total Daily Cost		$77.52

TRACTOR OPERATING COST

John Deere 420-23.5 hp 1956
$1,500 resale value

Useful life 5 years.

Depreciation $300/yr = $1.59/day	$ 1.59
Interest, Insurance, and Tax AAI x 10%	
$750 x 10% = $75.00	.40
Maintenance & Repair	
$600/yr	3.17
fuel	2.10
Operator	72.00
Total Daily Cost	$79.26

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[illegible] stem lodgepole pine stands. USDA For. Serv. Res. Pap. INT-2[illegible]1, [illegible]

Three different skidding methods---small rubber-tired skidder, horse, small tracked tractor--were compared in an overmature lodgepole pine stand in Montana.

KEYWORDS: timber harvesting, log skidding, lodgepole pine utilization.

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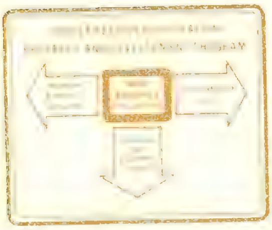

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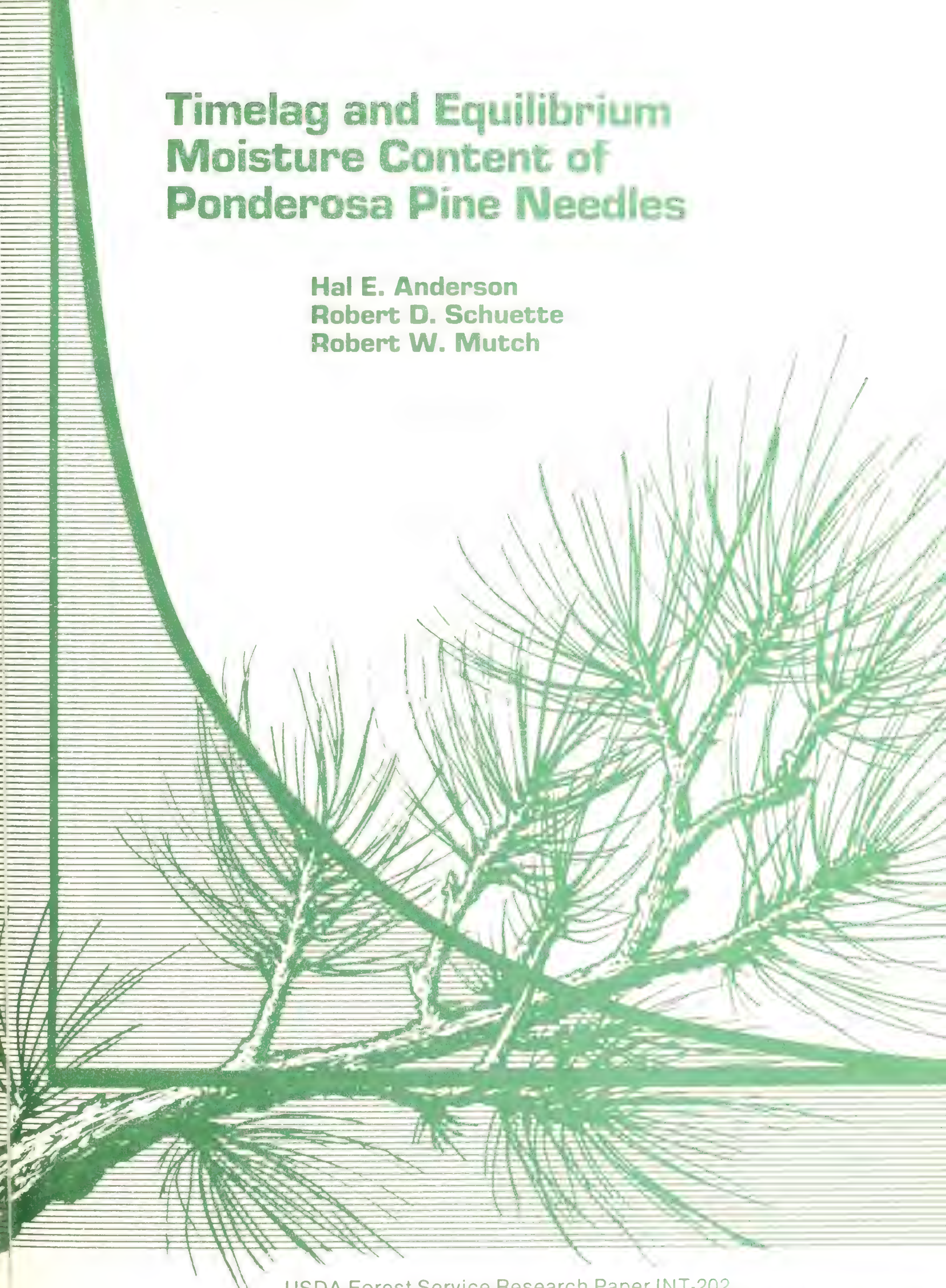

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TIMELAG AND EQUILIBRIUM MOISTURE CONTENT OF PONDEROSA PINE NEEDLES

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Sorption Time Constants for Single Ponderosa Pine Needles and Litter Beds 25

RESEARCH SUMMARY

Sorption studies of ponderosa pine (Pinus ponderosa Laws.) needles and litter beds of current year cast show a shorter response time and lower equilibrium moisture contents than most other conifer needle data in the literature. For conditions below fiber saturation, the response time is described best by considering the time for 95 percent of the total change in moisture content. Equilibrium moisture content can be estimated by an equation based on temperature and humidity, but type of vegetation must be considered.

Analysis of moisture response at the test conditions indicates that the moisture diffusivity of the needles and beds remains nearly constant for both adsorption and desorption.

INTRODUCTION

The ponderosa pine (*Pinus ponderosa* Laws.) timber type covers nearly 9 million cres in the Rocky Mountains. The needle litter cast by these trees produces a highly lammable fuel when conditions are dry. The capability for fires to start and spread epends largely on the moisture content of surface fuels and their response to environental changes. This report summarizes the results of laboratory tests to determine quilibrium moisture contents and adsorption-desorption timelags below fiber saturation f ponderosa pine needles. Conducting the tests at conditions below fiber saturation liminated consideration of the movement of free water and possible leaching of the eedles.

Research on fuel moisture over the past several years has added useful knowledge n fine forest fuels (Pěch 1968; Simard 1968a; 1968b; Nelson 1969; Van Wagner 1969 and 972; Mutch and Gastineau 1970; Blackmarr 1971; and Fosberg 1975). Equilibrium moisture ontents and timelags are the important moisture response characteristics of fine forest uels (Byram;[1] King and Linton 1963) and are required in fire-danger rating and fuels ppraisal systems. These two characteristics establish the moisture content at any ime, depending on the environmental conditions. Equilibrium moisture content (EMC) s defined as the moisture content finally attained uniformly throughout a material xposed to an atmosphere of fixed temperature and humidity. This occurs when the vapor ressure in the fuel equals the vapor pressure in the atmosphere. Moisture response ime, assumed to be an exponential response, is defined as the time required for a fuel o achieve 63.2 percent of the total change between its initial moisture content and MC. This can be expressed as 1 - 1/e of the difference between initial moisture content and EMC, where e is the base of natural logarithms.

The test results presented here establish the EMC values at 75° F (24° C), and the orption response times of needles and of fuel beds at three bulk densities, and report he effects of solar heating upon desorption. The tests with three fuel bed bulk densities were conducted at 80° F (27° C), with 90 and 20 percent relative humidity end oints to determine if the response times were different from response times of individal pine needles. The bulk densities (the load per unit area divided by the depth of he layer) matched findings for litter beds of ponderosa pine needles in western Montana Brown 1970).

---

[1] Byram, George M. 1963. An analysis of the drying process in forest fuel aterials. Paper presented at the 1963 International Symposium on Humidity and oisture, Washington, D.C., May 20-23, 1963. 38 p. (Unpublished report on file at he Southern Forest Fire Laboratory, Macon, Georgia 31208).

METHODS

Equipment

The EMC's of ponderosa pine needles were obtained over a range of relative humidities (16 to 88 percent) at ambient air temperature of 75° F ±5° (24° C ±2°) by means of two preconditioning cabinets and a final conditioning cabinet. One preconditioning cabinet provided a high humidity (95 percent) environment at ambient air temperature with open trays of water. The other preconditioning cabinet provided a hot-dry envirc ment of 2 to 6 percent relative humidity by simply heating the ambient air to 120° F (49° C). The final conditioning cabinet was maintained at a fixed relative humidity by use of saturated-salt solutions at the 75° F +5° ambient temperature. Temperatures within the cabinets were measured with mercury thermometers accurate to ±1° F and relative humidity was determined by standard psychrometer procedures and by dewpoint measuring equipment accurate to ±1° F.

The salt solutions used and the measured relative humidities for each were:

Salt :	LiCl	$MgCl_2$	$Mg(NO_3)_2$	NaCl	KNO_3
Percent relative humidity:	13	33	53	71	91

The moisture content of the needles was determined by withdrawing samples for xylene reflux distillation (Buck and Hughes 1939). Initial frequent sampling showed the moisture content to be within 1 percent moisture content of EMC after 1 week in mc cases. Two samples were taken at each measurement period.

The response time tests were conducted at 80° F (27° C), with step changes in hum ity from 90 to 20 percent and return. A conditioning cabinet was used to prepare the needle moisture content prior to the response test. Then, a programable environmenta chamber provided a shift in relative humidity so a moisture response could be induced The moisture response was measured as a weight change with unbonded, temperature-compensated strain gage transducers, load cells, and microscales. Sensitivity of the weighing systems was adjustable so weight changes to 0.01 g could be resolved. Value of air temperature, relative humidity, dewpoint, solar heat, and weight loss were recorded on charts for each moisture response test. The conditions in the environmenta chamber were controlled to ±2° F air temperature; ±2 percent at 20 percent relative humidity, and ±4 percent at 90 percent relative humidity; and ±0.01 of a solar consta

Airspeed within the test volume of the environmental chamber was found to average less than 0.50 mi/h and be rather turbulent. Variability above the center of a litter bed was found to be from near 0 to 0.60 mi/h. This may have affected the response time of the fuel beds by providing more turbulent airflow than occurs in natural sites. Air velocity within a needle litter bed with a bulk density of 0.94 lb/ft^3 (0.015 g/cc) averaged less than 0.160 ft/s (4.88 cm/s), or 0.11 mi/h.

Needles and Litter Beds

The needles used in all tests were first-year cast, collected in September and tober. The needles were sorted to remove broken needles and those separated from e fascicle. This tended to eliminate differences in moisture responses because of ysical defects. The general physical properties of these ponderosa pine needles are rown 1970):

Particle density	31.8 lb/ft^3 (0.51 g/cc ±0.046)
Surface area/volume	1,755 ft^2/ft^3 (57.57 [illegible])
Average thickness	0.027 in (0.0695 cm)
Shape factor	1.3

The litter beds of the needles for the EMC tests were placed in two wire screen ntainers to occupy a bulk density of 0.94 lb/ft^3 (0.015 g/cc). This bulk density is e medium value found by Brown (1970); the values for the light, medium, and heavy lk densities were, respectively, 0.31, 0.94, 2.81 lb/ft^3 (0.005, 0.015, and 0.045 cc) and were used for the tests of bulk density effects on moisture response times. e needles were loaded to a depth of 2 cm for each bulk density. Litter beds for the C tests were preconditioned at a high and at a low relative humidity until stabilized th their environment, then transferred to a final conditioning cabinet at a controlled midity and allowed to stabilize. Stabilized conditions were considered to be achieved en consecutive moisture content determinations were within ±1 percent moisture content.

Pine needles for the response time tests were preconditioned at a high humidity, 90 rcent relative humidity at 75° F (24° C). When the needles were stabilized in moisture ntent at approximately 23 percent moisture content ovendry weight, a precalculated quanty of needles was weighed and transferred to the programable environmental chamber. I the chamber, with conditions at 90 percent relative humidity and 80° F (27° C), the tter beds were made to the desired bulk density on special aluminum weighing trays th solid bottoms and sides to minimize airflow within the litter bed (fig. 1).

The chamber and litter beds were conditioned as shown in figure 2. Adsorption test tme was 24 to 48 hours, after which the litter beds were removed, weighed, and moisture ntent determined to provide a check of the weighing system's recorded weight change. ese needles were discarded and another quantity of conditioned needles used for the nxt test.

The environmental chamber controls and air conditioning equipment are capable of king the change for 90 to 20 percent relative humidity in 60 minutes and from 20 to percent relative humidity in 5 minutes. Some error in response time measurements n be caused by the response time of the chamber. Because pine needles have long rsponse times (Simard 1968b; Van Wagner 1969; Fosberg 1975), greater than 4 hours, erors should be small.

The influence of solar heating upon the moisture response was investigated by rnning a second series of sorption tests using the solar heating capability of the evironmental chamber. Nine overhead solar lamps provided the radiant heat simulating slar heating and were controlled by a pyroheliometer sensor and an electropneumatic rcorder controller. A 3-mil Cu-Cn thermocouple was attached to the surface of a nedle to monitor surface temperature on a strip-chart recorder. Solar heating was sarted at the beginning of the desorption run and maintained until the start of the asorption run, when it was turned off. An intensity of about 0.6 solar constant (.2 cal/cm^2-min) was used. These tests provided information on how response time was ifluenced by the additional temperature stress of solar heating.

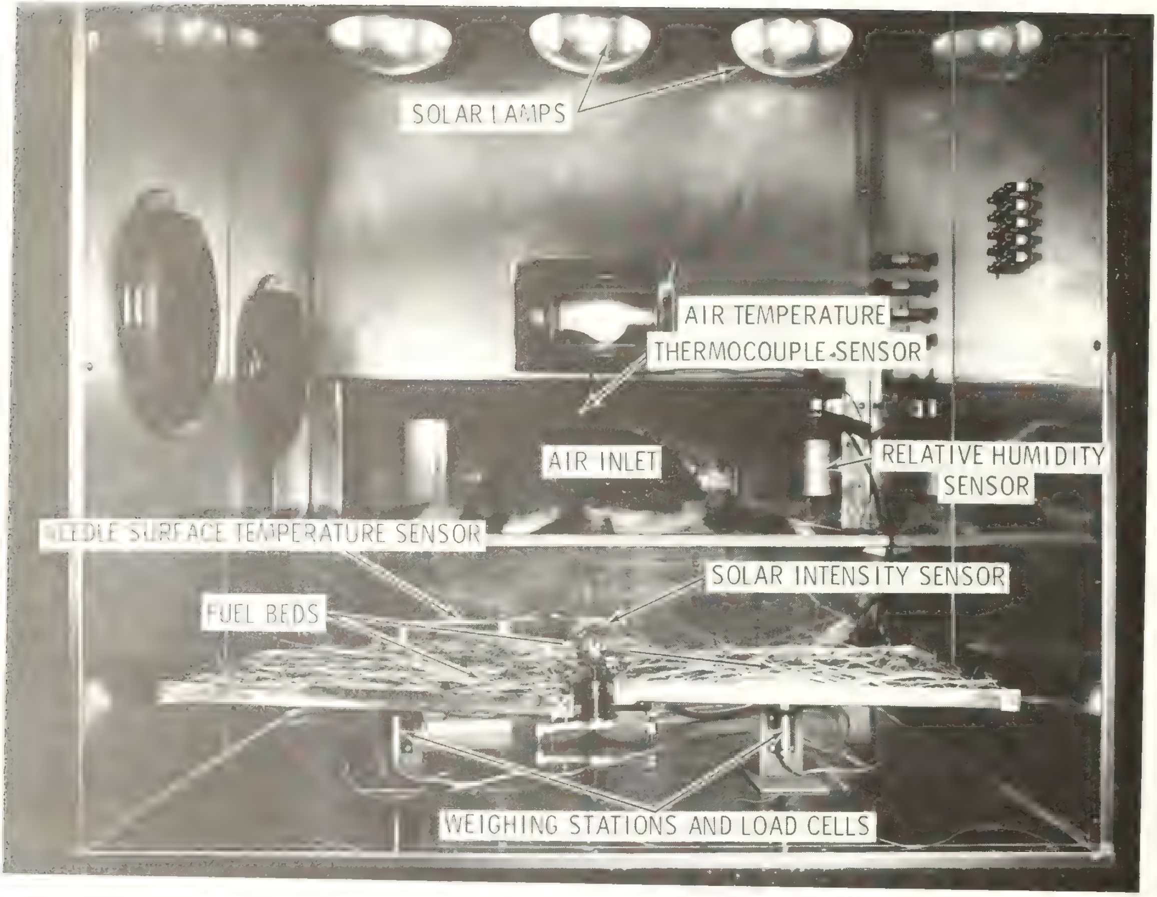

Figure 1.--Fuel bed located in environmental chamber.

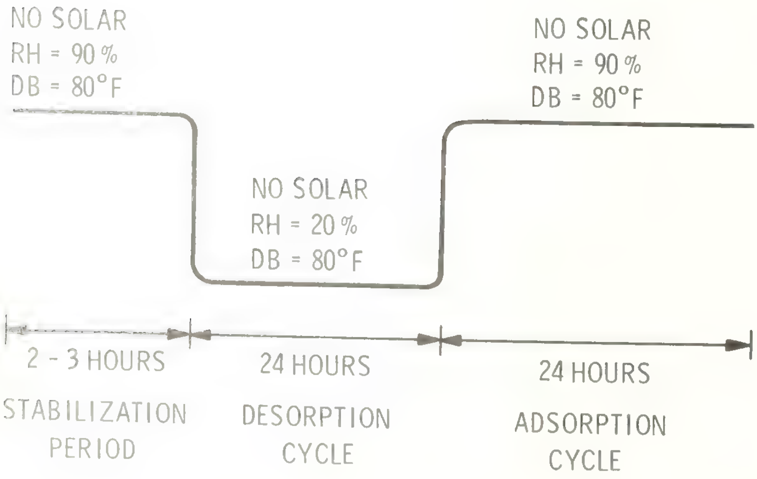

Figure 2.--The environmental conditions for the tests of moisture response time during first phase; a 0.6 solar constant was added for solar heating during the desorption cycle of the second phase of the tests.

RESULTS

Equilibrium Moisture Content

The sorption EMC tests were always started from a moisture content either higher or lower than any EMC expected. The desorption tests started from a high moisture content that ranged from 28.2 to 31.7 percent and averaged 29.6 percent. The adsorption tests started from a low moisture content between 2.6 and 3.4 percent that averaged 3.0 percent. The relative humidities used for conditioning and the EMC's that resulted are given in table 1. The differences between adsorption and desorption EMC's are less than 2.0 percent at humidities under 70 percent. Above 70 percent relative humidity, the difference became greater than 2.0 percent, approaching 3.5 percent at 90 percent relative humidity.

Table 1.--*Adsorption and desorption equilibrium moisture contents of ponderosa pine needles with starting moisture contents of 3.0 percent for adsorption and 29.6 percent for desorption*

Salt solution	Dry[1] bulb	Relative[2] humidity	Average adsorption moisture content	Average desorption moisture content	Hysteresis of moisture content
	°F	*Percent*			
LiCl	75	13	4.3 ±0.2	5.9 ±0.2	1.6
$MgCl_2$	75	33	7.5 ±0.4	9.0 ±0.0	1.5
$Mg(NO_3)_2$	75	53	10.2 ±0.2	11.9 ±0.1	1.8
NaCl	75	71	13.2 ±0.0	15.3 ±0.2	2.1
KNO_3	75	91	19.2 ±0.1	22.6 ±0.0	3.4

[1] Dry bulb temperature was maintained at 75°F ±5° (24° C ±2°).

[2] Relative humidity is the measured value and differs in some cases from values for chemically pure salts.

Moisture Response Time

Desorption and adsorption moisture response tests at 80° F (27° C) air temperature were run on individual needles and litter beds of the three bulk densities (fig. 3). The response time of materials to water vapor gradients is also called moisture timelag (Nelson 1969; Mutch and Gastineau 1970; Fosberg and Deeming 1971), and the moisture time constant (Van Wagner 1969). In each case, the expression is used to describe the exponential sorption process of the following equation (from Nelson 1969):

$$\frac{\bar{m} - m_e}{m_o - m_e} = E = K\exp(-t/\tau) \qquad (1)$$

(Con.)

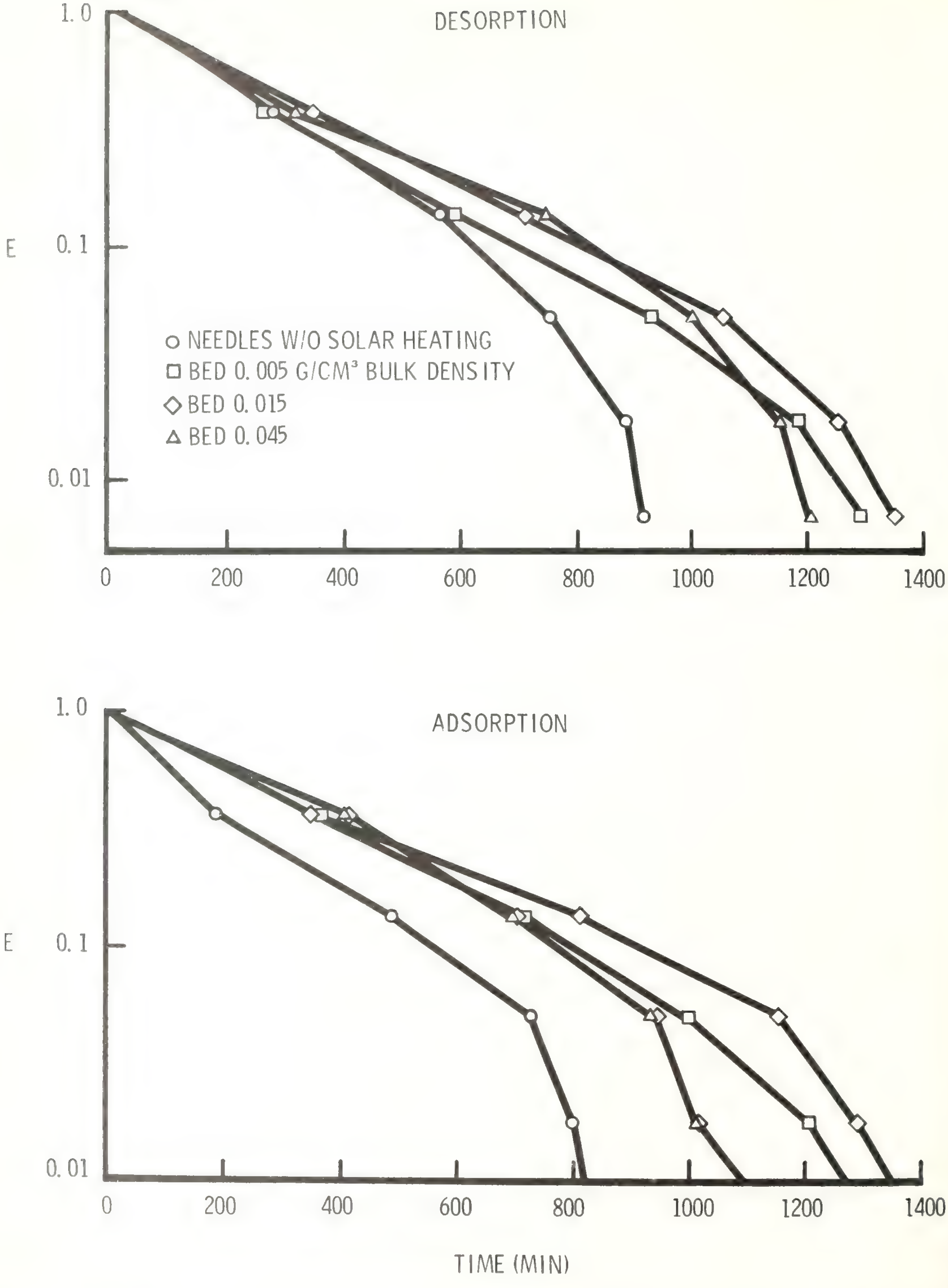

Figure 8.--Timelag response of ponderosa pine needles without solar heat (desorption).

where

$\bar{m}$ = average moisture content of needles or litter at time, t
m_e = equilibrium moisture content
m_o = initial moisture content
E = fraction of total evaporable moisture remaining in the fuel at time, t
K = dimensionless shape factor, assumed equal to 1.0
t = time, minutes
τ = response time, time constant, or timelag, minutes.

The descriptor, τ, represents the time required to proceed 63.2 percent, or (1 - 1/e), of the way to the total expected change. The time to achieve the total change can be broken in time periods. Each time period is the time to proceed 63.2 percent of the remaining portion of the total change and is tabulated in appendix table 5 for needles and table 6 for the adsorption and desorption tests without solar heating. The general trend shows an initial increase in time followed by a decrease as displayed in figure 4. This type of response has been reported by Nelson (1969), Mutch and Gastineau (1970), and Fosberg and others (1970).

The desorption tests with solar heating yielded shorter response times because solar heating at the 0.6 solar constant level increased needle surface temperature 23° F (-5° C). This caused a temperature gradient to be imposed on the vapor pressure gradient and shortened the response time, The adsorption runs following solar heating display a response not presently understood. The data for these runs are presented in table 7 of the appendix.

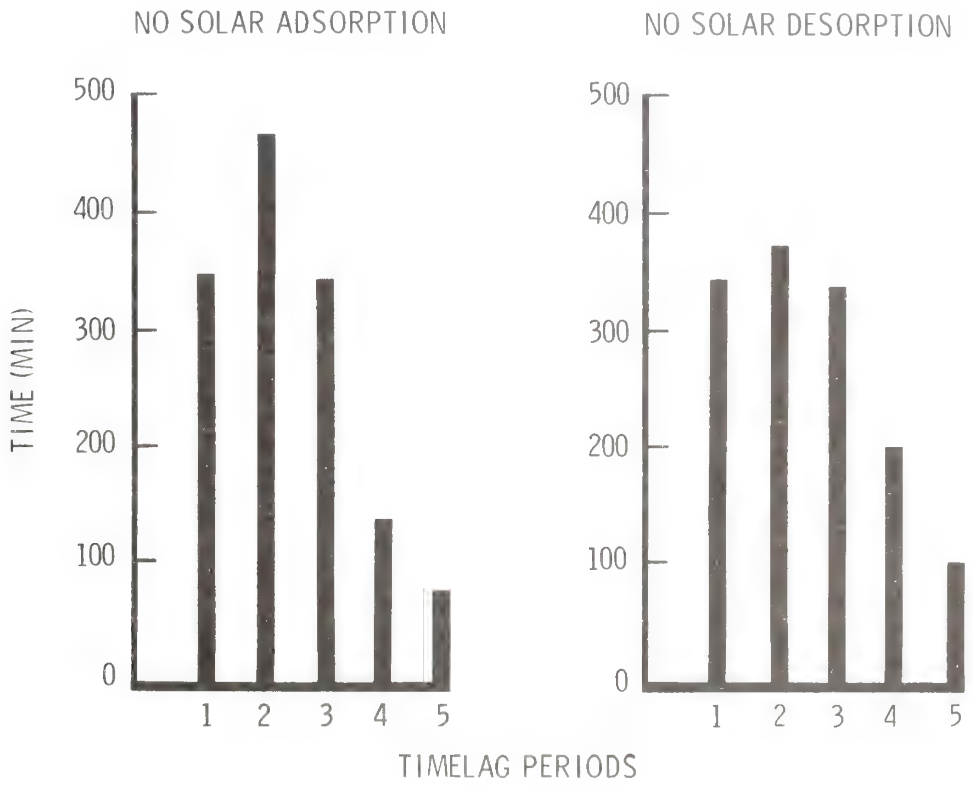

Figure 4.--Adsorption and desorption timelag periods for ponderosa pine needle beds at bulk density of 0.94 lb/ft³ (0.015 g/cc).

DISCUSSION

Equilibrium Moisture Content

A variety of studies of individual fuel types have been conducted to determine th EMC's of wildland fuels (Dunlap;[2] King and Linton 1963; Blackmarr 1971; Van Wagner 197 Britton and others 1973). However, Gisborne (1928) noted that tests by Dunlap[2] on woo samples of different species yielded results so nearly alike that a common EMC could be assigned to given relative humidities. Van Wagner (1972) found that leaf litter ha higher EMC's than common woods by about 3 percent moisture content. Differences betwe leaf litter types were felt to have little practical importance for predicting fine fu moisture content. However, Blackmarr (1971) and Van Wagner (1972) did observe an increase in EMC with weathering and aging which possibly is associated with the leaching of waxes and oils from the needles. The newly cast needles collected in September and October that we tested achieved EMC levels slightly lower than those found by Van Wagn for red pine needles.

The EMC data for ponderosa pine needles given in table 1 are plotted in figure 5 for adsorption and desorption. The curves displayed are from prediction equations generated from the data, according to the approach presented by Van Wagner (1972). Th general form of the prediction equation is:

$$EMC = aH^{b} + c \cdot EXP\,[(H - 100)/d] + m(T_{r} - T) \qquad (2)$$

where

EMC = equilibrium moisture content, percent ovendry weight
H = relative humidity, percent
T_r = reference temperature
T = temperature
a, b, c, d, m = coefficients dependent upon species, as noted by Van Wagner.

The last term adjusts for temperature which we did not test, but comparisons will be made to results obtained for ponderosa pine needles in other studies (Anderson 1964; Rothermel and Anderson 1966; Anderson 1969). These studies provide data on the adsorption equilibrium moisture content at 90° F (32° C) as ponderosa pine needles were conditioned for burning tests.

The coefficients of the terms in the equation were determined by first calculatin a least squares fit for a power function, aH^{b}, up to 60 percent relative humidity for the first term. The calculated values of EMC were subtracted from the observed EMC

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[2] Dunlap, M. E. Forest Products Laboratory, Madison, Wisconsin; work cited by Gisborne (1928), p. 29.

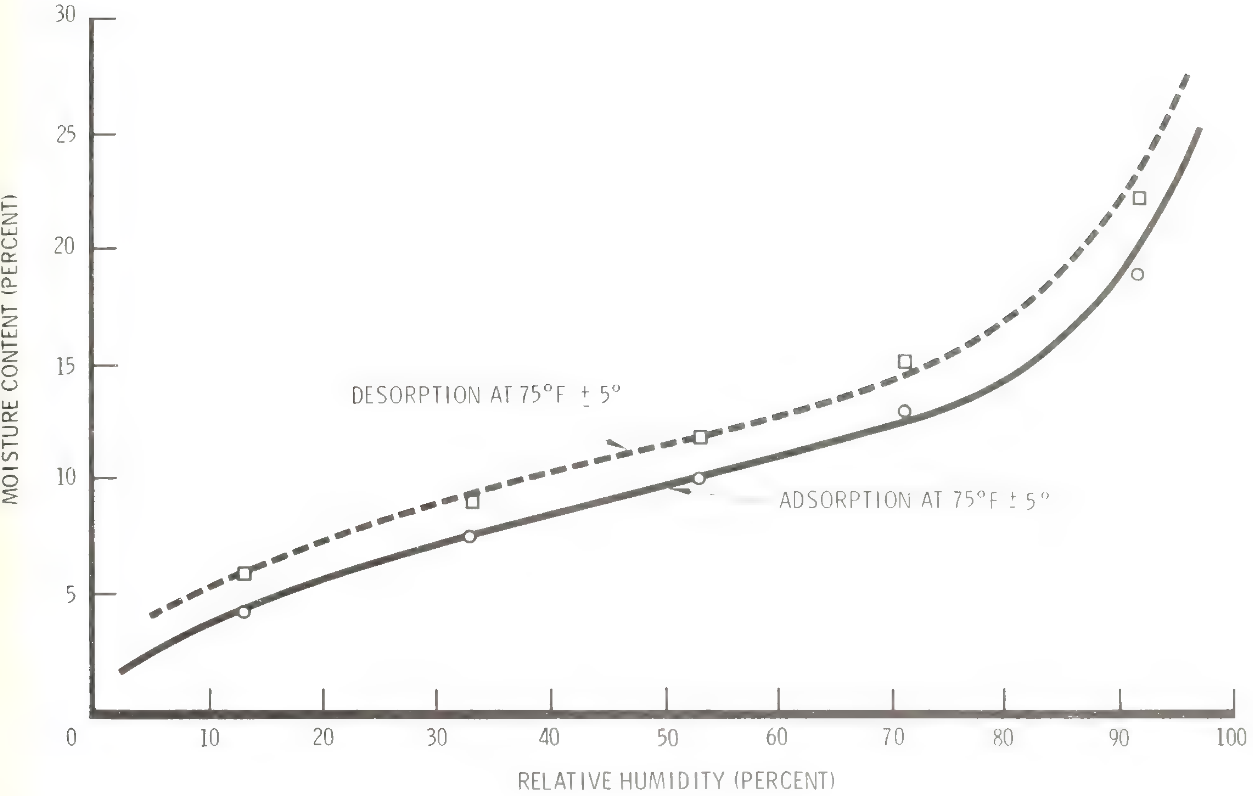

Figure 5.--Equilibrium moisture content data for adsorption and desorption with least squares fit curves from equations of the form, $EMC = aH^b + c \cdot EXP\ [(H - 100)/d]$ *for ponderosa pine needles.*

for each relative humidity and the difference used for a least squares fit to an exponential function, $c \cdot EXP\ [(H - 100)/d]$, from 50 percent relative humidity up to the maximum relative humidity. The overlap from 50 to 60 percent relative humidity provides a smooth transition and fit to the data. The coefficients, a, b, c, d, along with r_1 and r_2, correlation coefficients of moisture content to relative humidity for each portion of the equation, were determined to be:

	a	b	r_1	c	d	r_2
Adsorption	0.891	0.612	0.9998	17.54	8.91	0.9818
Desorption	1.651	.493	.9976	19.35	10.88	.9893

The curve in figure 5 shows the goodness of fit and shows the separation of the adsorption and desorption curves to be about 1.5 percent moisture content. Above 65 percent relative humidity, the separation continues to increase, reaching about 3.2 percent moisture content at 90 percent relative humidity.

Although the effect of temperature on EMC was not part of the tests reported here, the EMC curves were compared with earlier adsorption data (Anderson 1964; Rothermel and Anderson 1966; Anderson 1969). In the earlier tests, ponderosa pine needles were first ovendried. Then the needles were conditioned over saturated-salt solutions for different humidities at 90° F (32° C) until the needle moisture content had stabilized. These data were also fit to equation 2 and compared to the 75° F (24° C) data (fig. 6). A difference due to temperature appears from 20 to 80 percent relative humidity, but beyond these conditions the EMC values are essentially the same.

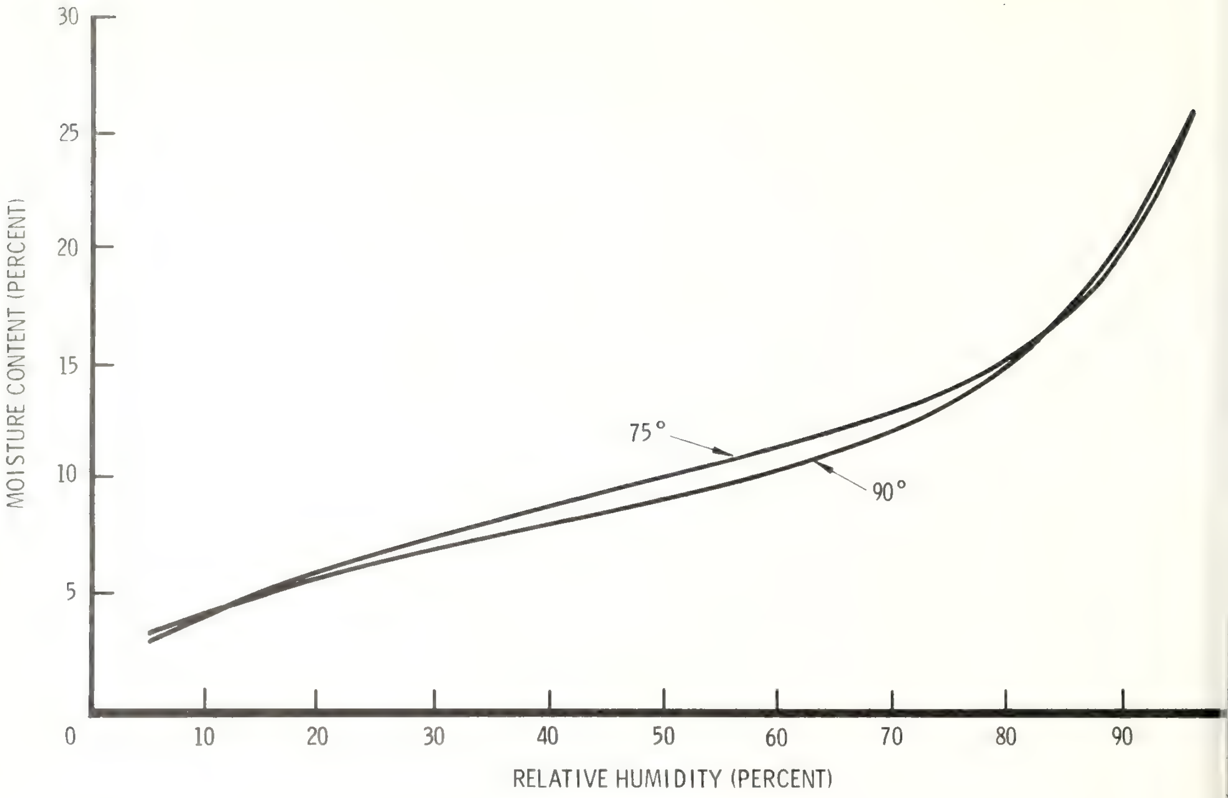

Figure 6.--Effect of temperature on adsorption EMC of ponderosa pine needles at 75° and 90° F.

Work by Spalt (1957) on basswood at 72° and 90° F (22° and 32° C) showed the sam trend to convergence at each extreme (Byram).[1] The influence of temperature on EMC a aged 0.056 percent EMC per degree Fahrenheit. In addition, Gisborne (1928) reported work by M. E. Dunlap for six fuel types that provided similar responses to temperatur A composite response for EMC change over the temperature range of 50° to 100° F (10° 38° C) provided a temperature factor of 0.050 percent EMC per degree Fahrenheit. Thi about half of what Van Wagner (1972) found for conifer litter, 0.113 percent EMC per degree Fahrenheit. The variation observed by Van Wagner suggests that additional stu is needed to identify the magnitude of the temperature influence. In addition, he no a difference between species in the EMC's established for given temperatures and humidities. For the ponderosa pine litter we tested, the EMC values for adsorption or des tion can be estimated by:

$$\text{Adsorption EMC} = 0.891\,H^{0.612} + 17.54\,\text{EXP}[(H - 100)/8.91] + 0.056(75 - T)$$

$$\text{Desorption EMC} = 1.651\,H^{0.493} + 19.35\,\text{EXP}[(H - 100)/10.88] + 0.056(75 - T)$$

where

H = relative humidity, percent
T = fuel surface temperature, °F.

Our EMC values were compared with EMC values for other fine forest fuels (King and Linton 1963; Stamm 1964; Rothermel and Anderson 1966; Anderson 1969; Blackmarr 1 Van Wagner 1972). Monterey pine displayed EMC's about 2 percent lower than ponderos pine which was 1 to 2 percent lower than other conifer needles. Grasses and both evergreen and deciduous hardwood leaf litter maintain higher EMC's than ponderosa pine needles. The difference in EMC values becomes greater as the relative humidity increases above 60 percent and the EMC divergence can be as high as 9 percent moisture content. Van Wagner (1972) concluded that all kinds of leaf litter have EMC's about 3 percent higher than the common woods; this difference in EMC is felt to be definitely important in fire-danger rating.

The sorption data for various pine needles are within 2.5 percent moisture content of each other in 53 percent relative humidity and 75° to 80° F (24° to 27° C). However, when other fine fuels like grasses, hardwood leaves, and wood splints are considered (Stamm 1964; Blackmarr 1971; Van Wagner 1972), the variation becomes sufficient to reduce the accuracy of fire-danger estimates. Examination of the data at 53 percent relative humidity showed the adsorption EMC values ranged from 8.3 to 12.3 percent and the desorption values ranged from 10.9 to 15.5 percent for a total range of 7.2 percent moisture content in EMC. This suggests a composite estimate of fine fuel moisture may be no closer than ±3.6 percent moisture content to the real value.

Comparing the fine fuel moisture content isotherm of the Canadian Forest Fire Weather Index with the 1-hour timelag fuel moisture of the United States' National Fire-Danger Rating System (NFDRS) shows a similar difference, approximately 4 percent, in predicted moisture content. This appears to be due to the type of fuels considered in establishing the moisture content response. The Canadian system is based on the litter fuels in their coniferous forest (Van Wagner 1974; Van Wagner and Pickett 1975) and the United States' system is based on studies of fine woody materials (Fosberg and Deeming 1971). The ponderosa pine needle data (fig. 7) agrees with the Canadian isotherm at low humidities, but holds to lower moisture contents at humidities above 30 percent and agrees with the National Fire-Danger Rating System 1-hour fuel moisture content.

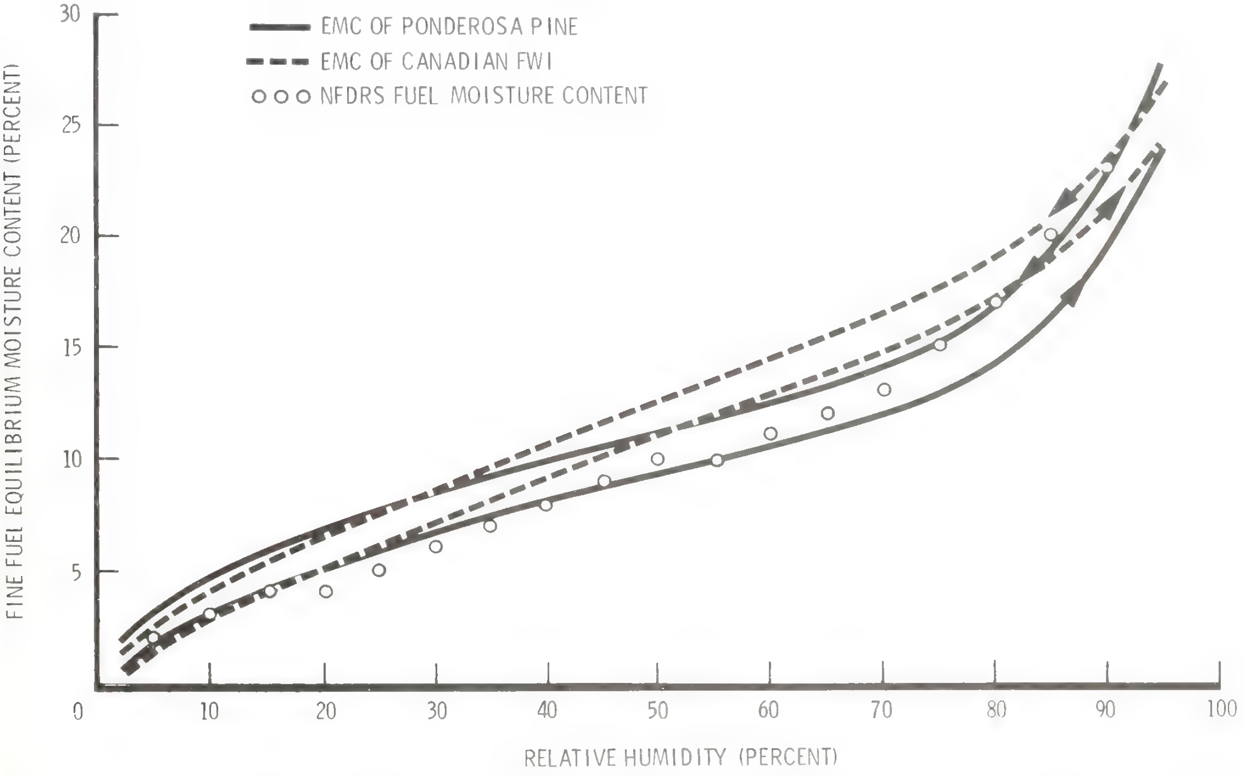

Figure 7.--Comparison of EMC values for ponderosa pine needles with fine fuel moisture content curve of Canadian Fire Weather Index and the USDA Forest Service NFDRS 1-hour timelag fuel moisture content data. Weather conditions -- 80° F and cloudy.

Allowance for specific fine fuel types may be necessary, particularly in areas where an index, such as the Ignition Index, is used administratively and is sensitive to fine fuel moisture content. For example, in an area where conditions can reach 80° F (27° C) and 20 percent relative humidity on a cloudy day, the NFDRS estimates nonliving fine fuel moisture content to be 4 percent. This may be 3 to 4 percent below the actual moisture content. This difference changes the Ignition Component from 65 to 38, which may be significant in a control unit's action plan. This type of sensitivity to fine fuel moisture content suggests that the measurement techniques and predictions of fine fuel moisture content be as accurate as possible.

Timelag

Ponderosa pine needles and litter beds exhibit similar timelag variability, but the similarity is less evident in litter bed test results (fig. 3). The variation in the timelag period may be due to the various factors influencing the diffusivity of the material. Byram[1] discussed control of moisture flow and thought that a forcing function of moisture content and saturation vapor pressure could effectively describe the change. This concept was expanded upon by Nelson (1969) and Fosberg (1970). Nelson showed that the diffusion theory could describe certain changes in moisture response of fine fuels, but such things as initial moisture content and relative humidity effects are not accurately predicted. Fosberg (1975) has developed a generalized approach to the theoretica solution using a timelag definition dependent upon physical properties of the material. He used boundary conditions that were difference approximations to the continuous change in temperature and relative humidity and noted that a different response time should be expected for each different set of initial conditions. The timelag has been associated with standard drying conditions of 80° F (27° C) and 20 percent relative humidity as not by Nelson (1969) for NFDRS use. For constant conditions, timelag is expressed as a function of material thickness, moisture diffusivity, and a dimensionless number, defined as a Fourier number for moisture by Byram[1]. For our tests, we are starting from the standard set of conditions to establish a stable method of evaluating timelag and to indicate the effect of bed bulk density on timelag.

Previous work and our test results show the timelag response is curvilinear, yielding shorter times for the fourth and fifth time periods. The latter periods involve small changes in moisture content, so small errors in moisture measurement result in large variations in the time measurement. For these reasons, and because the first three periods account for 95 percent of the total change and exhibit a near linear response on semilog graph paper (fig. 3; that is, a constant log drying rate) we determined the average timelag from the time to achieve a 95 percent change in moisture content. The time to achieve a 95 percent change represents three time periods, so one-third of that total time is the average timelag for a run. The mean timelag for each litter bed and sorption condition are given in table 2, along with the physical properties of each litter bed test condition.

Comparison of the results obtained using five time periods, three time periods, or the time for a 95 percent change of each run to compute an average and standard deviation showed that less variability occurred with the time to 95 percent change. For the litter beds with a bulk density of 0.015 g/cc, the standard deviation decreased from 125 min for five time periods to 69 min for three time periods to 48 min for a 95 percent change. Although greater stability is indicated for the latter method, the standard deviation indicates considerable variability in the vegetative material and litter beds; this indicates a number of runs are needed to obtain a reliable mean.

Table 2.--*Mean timelags for needles and litter beds of ponderosa pine needles based on the time for 95 percent of total change*

	Physical properties					Response time data			
Material	Thickness	Density	Packing ratio	Initial moisture content	Final moisture content	Arithmetic mean	Standard deviation	No. of runs	Standard error
	Cm	*G/cc*		– – – *Percent* – –		– – – [illegible] – – –			*Min*
				DESORPTION WITHOUT SOLAR					
Needles	0.0695	0.51	1.0	23.0	7.2	251.4	48.6	5	21.8
Bed	2.0	.005	0.0098	23.0	7.2	309.8	16.7	5	9.7
Bed	2.0	.015	.0294	23.0	7.2	350.4	48.2	6	19.7
Bed	2.0	.045	.0882	23.0	7.2	332.8	56.8	3	32.8
				ADSORPTION WITHOUT SOLAR					
Needles	.0695	.51	1.0	7.2	23.0	242.6	79.9	5	35.7
Bed	2.0	.005	.0098	7.2	23.0	333.1	91.8	[illegible]	64.9
Bed	2.0	.015	.0294	7.2	23.0	385.4	40.2	6	16.4
Bed	2.0	.045	.0882	7.2	23.0	314.5	14.4	3	8.3
				DESORPTION WITH SOLAR					
Bed	2.0	.005	.0098	23.0	7.2	243.3	70.4	4	35.2
Bed	2.0	.015	.0294	23.0	7.2	206.2	54.6	[illegible]	24.4
Bed	2.0	.045	.0882	23.0	7.2	154.0	24.5	4	12.3
				ADSORPTION AFTER SOLAR					
Bed	2.0	.005	.0098	7.2	23.0	382.9	54.6	4	27.3
Bed	2.0	.015	.0294	7.2	23.0	406.8	27.3	5	12.2
Bed	2.0	.045	.0882	7.2	23.0	411.3	18.1	4	9.1

The results for needles suggest nearly equal response times for desorption and adsorption. This timelag of 4.2 hours agrees with the needle timelag reported by Fosberg (1975) of 4.1 hours for freshly fallen ponderosa pine needles, as supplied by Blackmarr (1971). Data for other conifer needles, freshly cast, show variation in timelags:

Species	*Timelag*	*Drying condition*		*Reference*
	Hours	*°F*	*Percent relative humidity*	
Lodgepole pine	17.5	80	20	Blackmarr, in Fosberg (1975) (supported by our own tests)
Red pine	10.5	78 ±2	35 ±5	Van Wagner (1969)
Red pine	21.5	78 ±2	55 ±5	Simard (1968b)
Eastern white pine	17.5	78 ±2	55 ±5	Simard (1968b)
Jack pine	16.5	78 ±2	55 ±5	Simard (1968b)
White spruce	15.0	78 ±2	55 ±5	Simard (1968b)

The longer timelags may be partially due to the soaking before the test and the higher relative humidities used for end points. Only Blackmarr had end conditions similar to ours and although he presoaked the material, he obtained timelags comparable to ours.

Although we are not reporting results for weathered needles because tests are still being conducted, data in the literature show a dramatic shortening of the timelag:

Species	*Timelag*	*Drying condition*		*Reference*
	Hours	*°F*	*Percent relative humidity*	
Ponderosa pine	1.28	80	20	Fosberg (1975)
Lodgepole pine	1.01	80	20	Fosberg (1975)
Monterey pine	1.08	83	56	King and Linton (1963)
Red pine	4.20	78 ±2	35 ±5	Van Wagner (1969)
Red pine	7.00	78 ±2	55 ±5	Simard (1968b)
Eastern white pine	3.50	78 ±2	55 ±5	Simard (1968b)
Jack pine	4.00	78 ±2	55 ±5	Simard (1968b)
White spruce	5.00	78 ±2	55 ±5	Simard (1968b)

Variations in timelag may be due to the wax and resin content, as suggested by Van Wagner (1969). This could account for the shorter and variable timelags in weathered needles noted by Simard (1968b). It appears that the timelags are significantly different by species and weathering, which may be associated with the amount of waxes, oils, and varnishes on the surface and in the pores of the needles. Therefore, the results we are reporting probably only apply to freshly cast litter in ponderosa pine forests.

Generally, reports on timelags of fuels experiencing desorption or adsorption show the timelags to be longer for adsorption (Kerr and others 1971; Simard 1968b). Although the needle tests did not show this response, it did exist in the litter bed tests.

As the bulk density increased, the timelag increased but showed a leveling of timelag at the most dense value tested (fig. 8a). This leveling, or plateau, may be due to air velocities over and through the litter bed or may represent a zone of bulk densities where diffusion through the voids is limited by the moisture diffusivity of the particles. This consideration is pointed out by Fosberg (1975) in his theoretical development of heat and moisture flux in litter and duff. The responses obtained in this study tend to support the theoretical approach Fosberg has developed, but additional tests with varying bulk densities and litter depths are needed.

The desorption response of the litter bed with solar heating included appears to be inverse to the expected. Response time was found to become shorter as bulk density increased (fig. 8b) for desorption. With adsorption conditions established and solar heating turned off, the response is similar to previous adsorption tests. Some lengthening of timelag was observed, reflecting the thermal relaxation of stress back to ambient air temperature.

Little moisture response data are available to compare with theoretical developments such as Fosberg's (1975), but the litter bed tests we conducted at a bulk densit of 2.81 lb/ft^3 (0.045 g/cc) were compared to the profiles Fosberg (1975) presented in figure 8 of his paper. Since the experimental measuring methods we used provided the average moisture content of the bed, comparison to Fosberg's theoretical results required averaging his moisture content profile at each depth over time. Both thermal

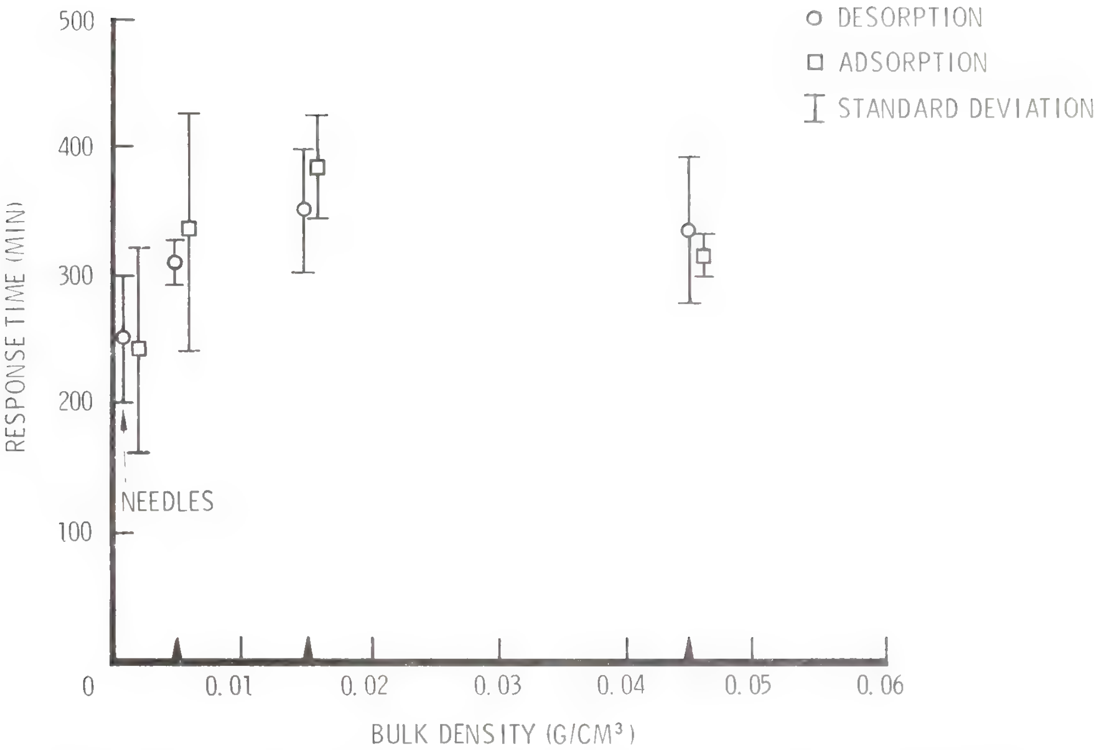

Figure 8A.--Response of timelag to changes in litter bed bulk density.

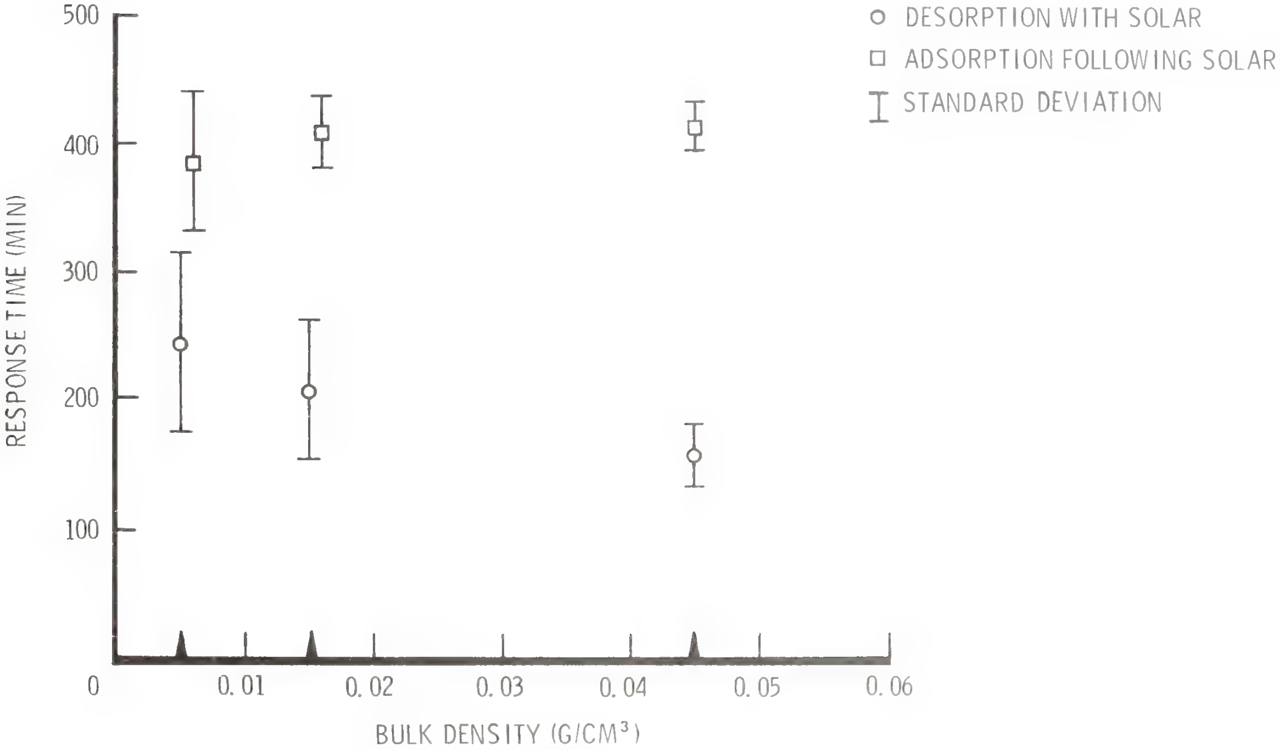

Figure 8B.--Response of timelag to changes in litter bed bulk density with or following solar heating.

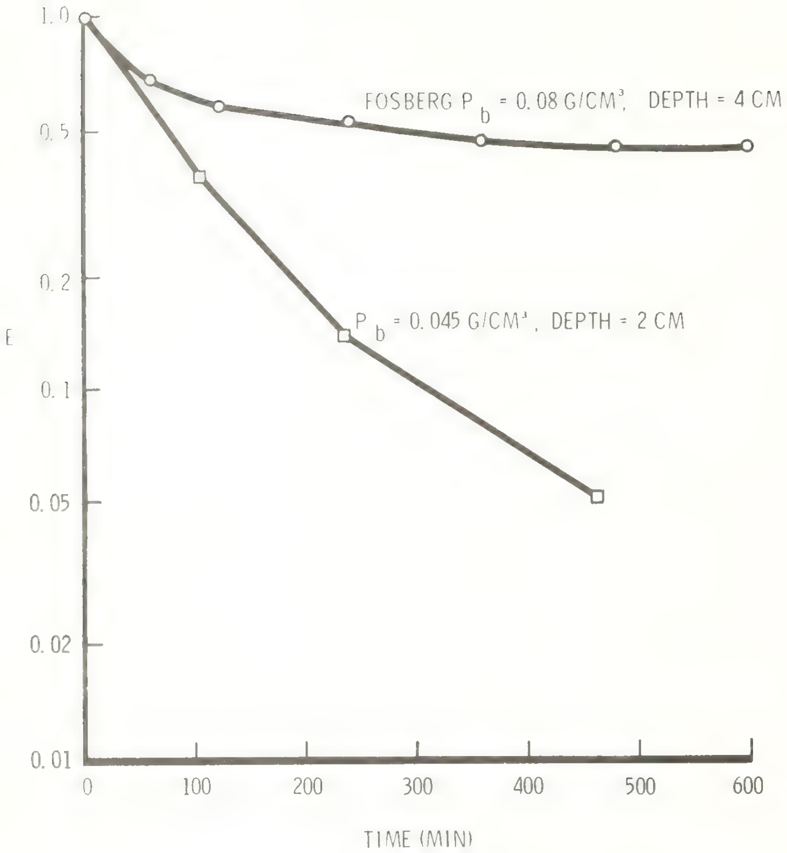

Figure 9.--Comparison of average moisture content for theoretical analysis of moisture content profile (Fosberg 1975) and experimental results for litter bed of ponderosa pine.

and moisture stress were imposed in both situations and the comparison shows that the theoretical approach does predict the timelag to increase with each successive time period (fig. 9). This behavior is found at each bulk density when solar heating was used and reflects the initial response to both the temperature and moisture changes followed by the response to moisture only, which has a longer timelag.

Moisture Diffusivity

It has been noted earlier that the timelag did not remain constant during the sorption process and the differences could be traced to the assumptions made in the theory of homogeneous physical properties and the diffusivity. Fosberg (1975) discussed the diffusivities involved and utilized them in the development of his theoretical approach. At least three degrees of diffusivity need to be considered; the diffusivity of the particles, of the voids, and the effective diffusivity of the litter layer.

For individual particles, it has been shown that the Fourier number for moisture describes the relationship of timelag, diffusivity, and particle thickness (Fosberg 1970; Fosberg and others 1970):

$$F_o = \nu/\lambda R^2 \qquad (3)$$

where

F_o = Fourier number, dimensionless

ν = diffusivity, cm^2/s

R = thickness, cm

$1/\lambda = \tau$ = timelag, s

λ = timelag reciprocal or decay coefficient, s^{-1}.

This equation relates to the equation for the integral diffusion coefficient, D, described by Stamm and Nelson (1961) and Stamm (1964). In turn, Stamm states this resulted from Fick's general diffusion equation.

Stamm's equation for the integral diffusion coefficient can be rearranged to a form similar to equation (3):

$$\bar{D} = \nu = \frac{\pi E^2}{16}\frac{a^2}{t} \tag{4}$$

where

E = fraction of total change accomplished
a = R = thickness, cm
t = time for change accomplished
π = 3.1416.

Rearrangement and common defining of terms lead to:

$$\frac{\pi E^2}{16} = \frac{\nu t}{R^2} \tag{5}$$

where the right-hand side is the same as the right-hand side of equation (3) except t is the time for the fraction of the total change, E, instead of $1/\lambda$ or τ, which is the timelag. Since the timelags for the data reported in this paper were calculated from the time for 95 percent of the total change, the diffusivity of the particles and the litter beds can be determined for the same conditions using equation (5):

$$\nu = \frac{\pi E^2}{16}\frac{R^2}{t} = \frac{\pi(0.95)^2}{16}\frac{R^2}{t} = 0.177\frac{R^2}{t}. \tag{6}$$

The quantity, $\pi E^2/16$, of equations (4), (5), and (6) is a form of the Fourier number. With E equal to 95 percent of the total, the product is 0.177. This value agrees closely with values calculated from figure 2 of Fosberg's 1970 paper on drying rates of heartwood. If we could accurately determine when the total change has occurred, the value should approach 0.1963, $\pi/16$.

A summary of the timelags, thicknesses, and diffusivities is given in table 3. The range of diffusivities is shown in figure 10 which shows the diffusivities of the particles, the litter beds, and the voids. Both desorption and adsorption diffusivity changes with time are shown and indicate a common diffusivity is approached by both sorption processes. The diffusivities calculated using three timelag periods and 95 percent of the total change are slightly lower than diffusivities computed from specific fractions of total change and the time for the change. However, the differences do not appear significant.

The diffusivity of the voids was calculated from the diffusivity of free air at the test conditions and considering the porosity of the litter beds. The free air diffusivity was determined by the empirical equation used by Stamm and Nelson (1961):

$$\nu_o = 0.22\left(\frac{T}{273}\right)^{1.75}\left(\frac{760}{P}\right)\text{cm}^2/\text{s} \tag{7}$$

where

T = temperature, °K
P = pressure, mm Hg = 760 EXP $[-(gh)/(RT_m)]$ (8)
g = 981 cm/s^2
h = elevation, cm
R = gas constant for air, $2.87 \times 10^6 \ \frac{\text{cm} - \text{g}}{\text{g} - {}^\circ\text{K}}$
T_m = temperature at test, 300° K.

Table 3.--Moisture response properties of ponderosa pine needles and litter beds

Material	Density	Packing ratio	Thickness	Timelag	Diffusivity
	G/cm^3		*Cm*	*S*	*Cm*^{2}*/s*
		DESORPTION WITHOUT SOLAR			
Needles	0.51	1.0	0.0695	15,084	1.89×10^{-8}
Bed	.005	.0098	2.0	18,588	1.27×10^{-5}
Bed	.015	.0294	2.0	21,024	1.12×10^{-5}
Bed	.045	.0882	2.0	19,968	1.18×10^{-5}
		ADSORPTION WITHOUT SOLAR			
Needles	.51	1.0	.0695	14,556	1.96×10^{-8}
Bed	.005	.0098	2.0	19,986	1.18×10^{-5}
Bed	.015	.0294	2.0	23,124	1.02×10^{-5}
Bed	.045	.0882	2.0	18,870	1.25×10^{-5}
		DESORPTION WITH SOLAR			
Bed	.005	.0098	2.0	14,598	1.62×10^{-5}
Bed	.015	.0294	2.0	12,372	1.91×10^{-5}
Bed	.045	.0882	2.0	9,240	2.56×10^{-5}
		ADSORPTION AFTER SOLAR			
Bed	.005	.0098	2.0	22,974	1.03×10^{-5}
Bed	.015	.0294	2.0	24,408	9.68×10^{-6}
Bed	.045	.0882	2.0	24,678	9.57×10^{-6}

For the Missoula area, the diffusivity of the free air was calculated to be 0.292 cm^2/s. For the voids within the fuel beds, the approach cited by Fosberg (1975) was used. Work by Millington and Shearer (1971) shows the reduction in diffusivity to be a function of bed porosity:

$$\nu / \nu_o = \phi^{2x} \tag{9}$$

and the exponent, x, is defined by

$$\phi^{2x} \equiv 1 - (1 - \phi)^x, \text{ tortuosity factor} \tag{10}$$

where

ν_o = free air diffusivity, cm^2/s
ν = void diffusivity, cm^2/s
ϕ = bed porosity, fraction of volume, dimensionless.

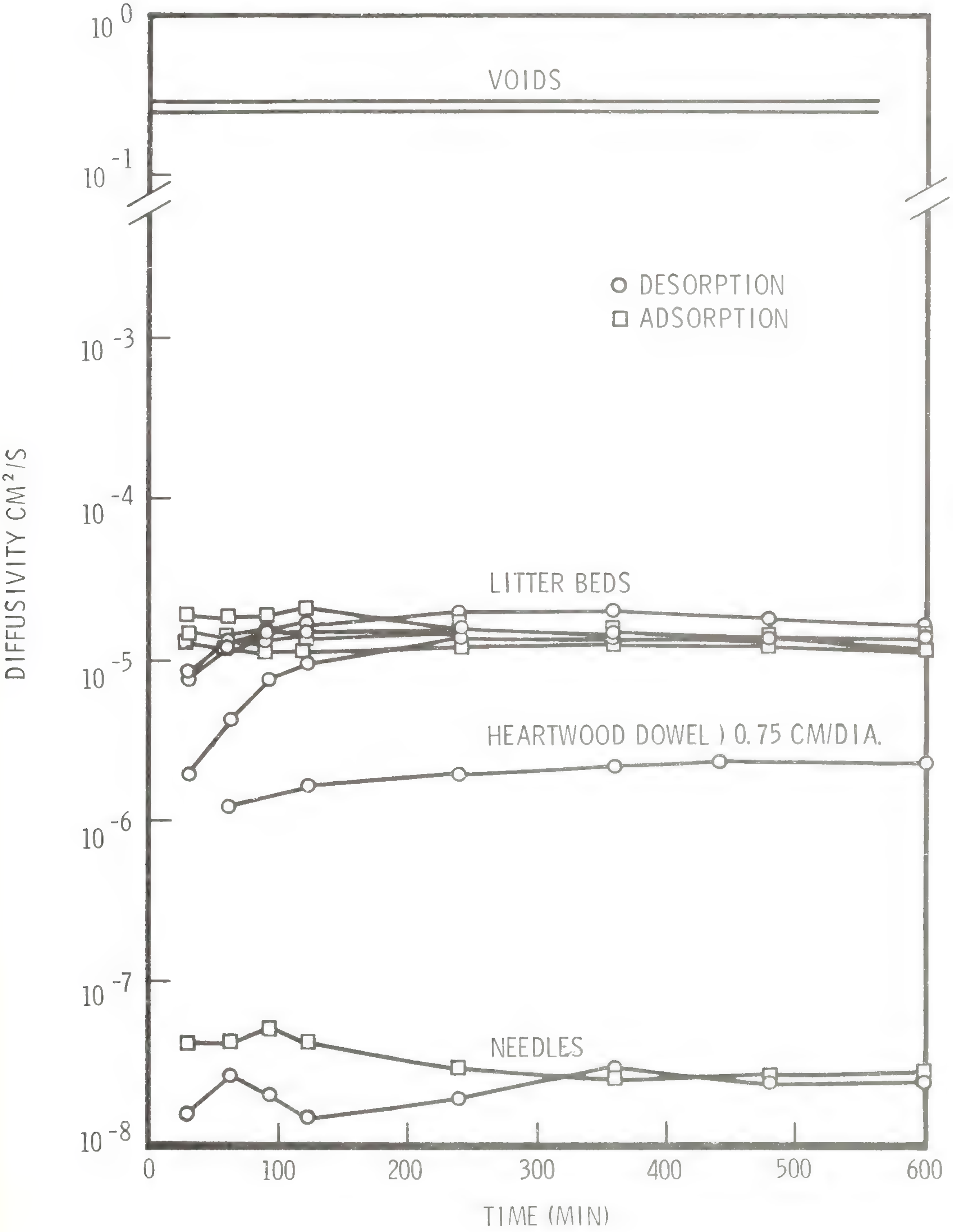

Figure 10.--Range of diffusivities determined for ponderosa pine needles, litter beds, and the voids within the bed.

Table 4.--*Comparison of diffusivity calculated for ponderosa pine litter beds under desorption conditions*

Physical properties	Fosberg (1975)		Anderson, Schuette, and Mutch		
	1	2	1	2	3
Fuel depth, H, (cm)	3	4	2	2	2
Bulk density, P_b, (g/cc)	0.08	0.08	0.005	0.015	0.045
Needle timelag, t, (s)	4,608	4,608	15,084	15,084	15,084
Free air diffusivity, ν_o, (cm^2/s)	0.313	0.313	0.292	0.292	0.292
Porosity, ϕ, (dimensionless)	0.830	0.830	0.990	0.971	0.912
Tortuosity factor, ϕ^{2x}, (dimensionless)	0.748	0.748	0.983	0.950	0.861
Void diffusivity, ν, (cm^2/s)	0.234	0.234	0.287	0.278	0.251
Litter bed timelag, t, (s)	4,248	7,560	18,588	21,024	19,968
Litter bed diffusivity, $\bar{\nu}$, (cm^2/s)	1.25×10^{-4}	1.25×10^{-4}	1.27×10^{-5}	1.12×10^{-5}	1.18×10^{-5}

The free air diffusivity was reduced by the above factor and the results for the litter beds compared to the predicted response of weathered ponderosa pine litter beds presented by Fosberg (1975) in his figures 2 through 5, table 4. Although the void diffusivities are not greatly different, the bed diffusivities differed by a factor of 10 when computed by equation (6). This is primarily a result of the longer particle and bed timelags existing in our experiments.

According to figure 9 of Fosberg's paper (1975), our experimental conditions appear to be at the limits of the theoretical considerations because our bed depth or thickness of 2 cm is in the zone where response time or timelag decreases as bulk density increase As Fosberg notes, the timelag should increase as the bulk density increases and bed porosity decreases. Our results do not show a strong relationship between timelag and bulk density for the fuel loadings and depth we used.

Discussion of empirical refinements to improve the description of moisture diffusivity by Bramhall (1973) has proposed the inclusion of diffusivity as a linear function of moisture content. However, for litter beds and needles of ponderosa pine, the diffusivity appears to remain constant except for early in the sorption change. The same response of diffusivity is obtained using equation (6), as indicated in figure 10, for ponderosa pine heartwood dowels (Fosberg and others 1970). The value of 2.3×10^{-6} cm^2/s is higher than the value cited in the above work but is comparable to values cited by Stamm (1964) for various woods. The variation in diffusivity does appear to be nearly constant by species of material as long as the physical properties do not change. Then equation 3, 6, or equation 30 presented by Fosberg (1975) could be used to estimate the response time for a given fuel situation. If diffusivity is nearly constant and the thickness of material is known, response time can be readily calculated For a given weather change in temperature and humidity, the time response can be considered with the EMC equations to estimate the moisture content of the litter and as related to flammability.

CONCLUSIONS

The equilibrium moisture content response curve of freshly cast ponderosa pine needles is lowest of the conifer needle data examined, except for Monterey pine. Differences between adsorption and desorption are slight (<1.5 percent) to 60 percent relative humidity, and the spread increases with increasing relative humidity. The EMC response can be described mathematically if temperature and humidity are known. Woody materials, such as twigs and splints of wood, maintain lower EMC's, while grasses and other herbaceous materials have higher EMC's, as much as 3 to 4 percent.

Temperature effects on EMC seem to vary by species and range from 0.050 to 0.113 percent moisture content per degrees Fahrenheit. Other changes in the litter material, suc as crude fats, density, or possibly shape caused by weathering and aging, result in shifts in EMC values. Sufficient data are not available to fully assess these influences. However, they seem to influence both EMC values and timelag response.

Ponderosa pine needles, freshly cast, were found to have shorter timelags than other freshly cast conifer needles; approximately 4 hours as compared to 10 to 17 hours. It was noted in the literature that a year's weathering changes the timelag to a much shorter value, on the order of 1 hour. Although the change is felt to be associated with the leaching of the crude fat and other extractives, it is not known how rapidly the change in timelag occurs or what has been removed from the needles.

EMC and timelag values for ponderosa pine needles are sufficiently different from other species as to significantly affect the flammability of an area. The influence upon systems to assess fire danger should be determined so the use of fire-danger rating components and indices is as accurate as possible.

Use of the experimental data for fraction of moisture change and the time for the change showed moisture diffusivity to remain nearly constant during the response to the test conditions. However, just as air diffusivity is changed by pressure and temperatures, so may the moisture diffusivity of the litter material be changed. For litter beds with bulk densities between 0.31 lb/ft^3 (0.05 g/cc) and 2.81 lb/ft^3 (0.045 g/cc) the diffusivity was found to be 1.2×10^{-5} cm^2/s and for newly cast needles, 2.0×10^{-8} cm^2/s.

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APPENDIX

Sorption Time Constants for Single Ponderosa Pine Needles and Litter Beds

Table 5.--*Sorption time constants (in minutes) for a single ponderosa pine needle. Desorption conditions: 80° F (27° C) and humidity change from 90 to 20 percent. Adsorption conditions: 80°F and humidity change from 20 to 90 percent*

REPLICATES	Time period					Average
	1	2	3	4	5	
Desorption						
1	260	272	68	374	29	201
2	225	119	264	63	24	139
3	430	238	222	74	29	199
4	320	358	222	74	29	201
5	150	450	173	76	32	176
Average	277	287	190	132	29	
Adsorption						
1	110	169	141	134	29	117
2	90	317	213	62	24	141
3	379	179	102	37	15	142
4	148	206	582	87	36	212
5	192	650	161	41	17	212
Average	184	304	240	72	24	

Table 6.--*Sorption time constants (in minutes) for ponderosa pine needle litter beds. Desorption conditions: 80° F (27° C) and* [illegible]

REPLICATES	Time period 1	2	3	4	5	Average
	LOADING: BULK DENSITY 0.005 g/cm					
Desorption						
1	271.6	390.0	265.1	100.8	108.7	227.2
2	250.4	281.5	348.7	350.8	124.8	271.2
3	280.5	303.2	397.0	299.6	93.8	274.8
Average	267.5	324.9	336.9	250.4	109.1	
Adsorption						
1	[1] --	--	--	--	--	--
2	443.7	355.9	394.4	149.8	60.9	280.9
3	285.7	343.9	175.1	255.5	152.2	242.5
Average	364.7	349.9	284.8	202.7	106.6	
	LOADING: BULK DENSITY 0.015 g/cm					
Desorption						
1	356.3	439.6	482.1	87.5	40.1	281.1
2	285.0	317.5	346.8	294.7	96.2	268.0
3	451.8	372.6	298.8	129.0	91.8	268.8
4	384.6	434.4	243.0	216.0	84.0	272.4
5	264.4	315.0	279.3	320.9	148.9	265.7
6	307.3	346.4	383.0	149.3	139.7	265.1
Average	341.6	370.9	338.8	199.6	100.1	
Adsorption						
1	452.9	404.2	369.8	65.4	27.0	263.9
2	291.7	458.0	184.7	335.9	107.5	275.5
3	343.2	472.8	444.0	132.0	30.0	284.4
4	292.2	403.8	462.0	78.0	120.0	271.2
5	307.5	459.3	353.8	118.2	103.6	268.5
6	393.9	595.8	247.4	89.6	71.7	279.7
Average	346.9	465.6	343.6	136.5	76.6	
	LOADING: BULK DENSITY 0.045 g/cm					
Desorption						
1	271.1	351.8	194.4	120.0	52.4	197.9
2	312.8	413.9	296.0	210.2	55.1	257.6
3	371.5	514.5	269.2	120.2	66.1	268.3
Average	318.5	426.7	253.2	150.1	57.9	
Adsorption						
1	474.8	239.6	277.5	24.1	333.2	269.8
2	353.6	324.5	230.7	45.1	37.4	198.3
3	374.2	358.9	196.3	133.3	48.9	222.3
Average	401.0	307.7	234.8		139.8	

[1] Malfunction in the environmental chamber during absorption phase prevented the accumulation of data for the first run.

Table 7.--*Sorption time constants (in minutes) for ponderosa pine needle litter beds. Desorption conditions with solar hear: 80° F (27° C), 90 to 20 percent relative humidity, 0.6 solar constant. Adsorption conditions following solar heat: 80° F, 20 to 90 percent relative humidity, 0.0 solar constant*

REPLICATES	Time period					Average
	1	2	3	4	5	
	LOADING: BULK DENSITY 0.005 g/cm^3					
Desorption						
1	200.0	329.9	496.4	305.9	68.2	280.1
2	142.3	187.6	205.9	371.0	131.7	207.7
3	184.2	262.9	270.3	431.5	130.3	255.8
4	150.0	230.1	260.5	337.1	124.8	220.5
Average	169.1	252.6	308.3	361.4	113.7	
Adsorption						
1	297.2	518.3	521.4	73.2	19.0	285.8
2	320.3	423.7	263.3	379.3	33.8	284.1
3	360.5	563.5	310.7	92.0	33.8	272.1
4	291.7	388.9	334.9	198.9	28.9	248.6
Average	317.4	473.6	357.6	185.8	28.9	
	LOADING: BULK DENSITY 0.015 g/cm^3					
Desorption						
1	104.5	168.6	170.9	243.5	298.6	197.2
2	161.3	185.4	425.6	229.4	327.5	265.8
3	147.6	157.4	480.4	504.4	95.1	277.0
4	121.2	212.4	126.6	172.8	279.0	182.4
5	161.4	200.4	270.0	154.2	120.0	181.2
Average	139.2	184.8	294.7	260.9	224.0	
Adsorption						
1	535.1	418.9	276.5	137.7	47.5	283.1
2	473.0	434.9	203.7	93.9	34.5	248.0
3	483.6	520.0	336.2	70.8	18.6	285.8
4	444.0	426.0	325.8	64.2	132.0	278.4
5	462.0	478.0	283.8	126.0	42.0	278.4
Average	479.5	455.6	285.2	98.5	54.9	
	LOADING: BULK DENSITY 0.045 g/cm^3					
Desorption						
1	99.4	116.7	222.2	216.7	551.3	241.2
2	82.1	111.1	252.5	499.7	199.1	228.9
3	127.0	175.6	264.9	588.5	181.9	267.6
4	103.9	121.1	171.6	222.5	560.8	236.0
Average	103.1	131.1	227.8	381.8	373.3	
Adsorption						
1	520.8	472.0	264.1	102.9	47.1	281.4
2	504.2	466.6	233.0	150.2	54.4	281.7
3	604.5	490.8	203.2	105.6	22.7	285.4
4	578.1	419.7	179.1	188.2	41.9	281.4
Average	551.9	462.3	219.9	136.7	41.5	

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Sorption studies of ponderosa pine (*Pinus ponderosa* Laws.) needles and litter beds of current year cast show a shorter response time and lower equilibrium moisture contents than most other conifer needle data in the literature.

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COST, PERFORMANCE, AND ESTHETIC IMPACTS OF AN EXPERIMENTAL FOREST ROAD IN MONTANA

Rulon B. Gardner

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RESEARCH SUMMARY

A study on the Coram Experimental Forest in Montana was designed to assess the environmental impacts of harvesting and attendant road construction. The objective of the road portion of the study was to locate, design, and construct a road with reduced impacts (compared to standard practice) on the environment that would still serve the near-minimum needs of the projected traffic volumes, vehicle sizes, and logging equipment (skyline logging), and to evaluate the costs and impacts.

A single-lane (14-foot (4.27-m) finished surface with a 3-foot (0.91-m) dtich) road was constructed along the general contour, turnouts were fitted to the terrain and were not intervisible, and landings were not constructed. Other selected design criteria were also used to reduce impacts.

Skyline harvesting was accomplished from the single-lane road without undue difficulty, and it continues to serve traffic needs. Comparison of the road with adjacent, older forest roads incidates a major improvement in esthetic acceptability.

A comparison of hauling costs with a double-lane road, using traffic volumes appropriate for the area (10 VPH, 1/2 logging trucks), showed costs would be about \$2.35/M bd. ft. (\$0.59/m^3) higher for the single-lane road.

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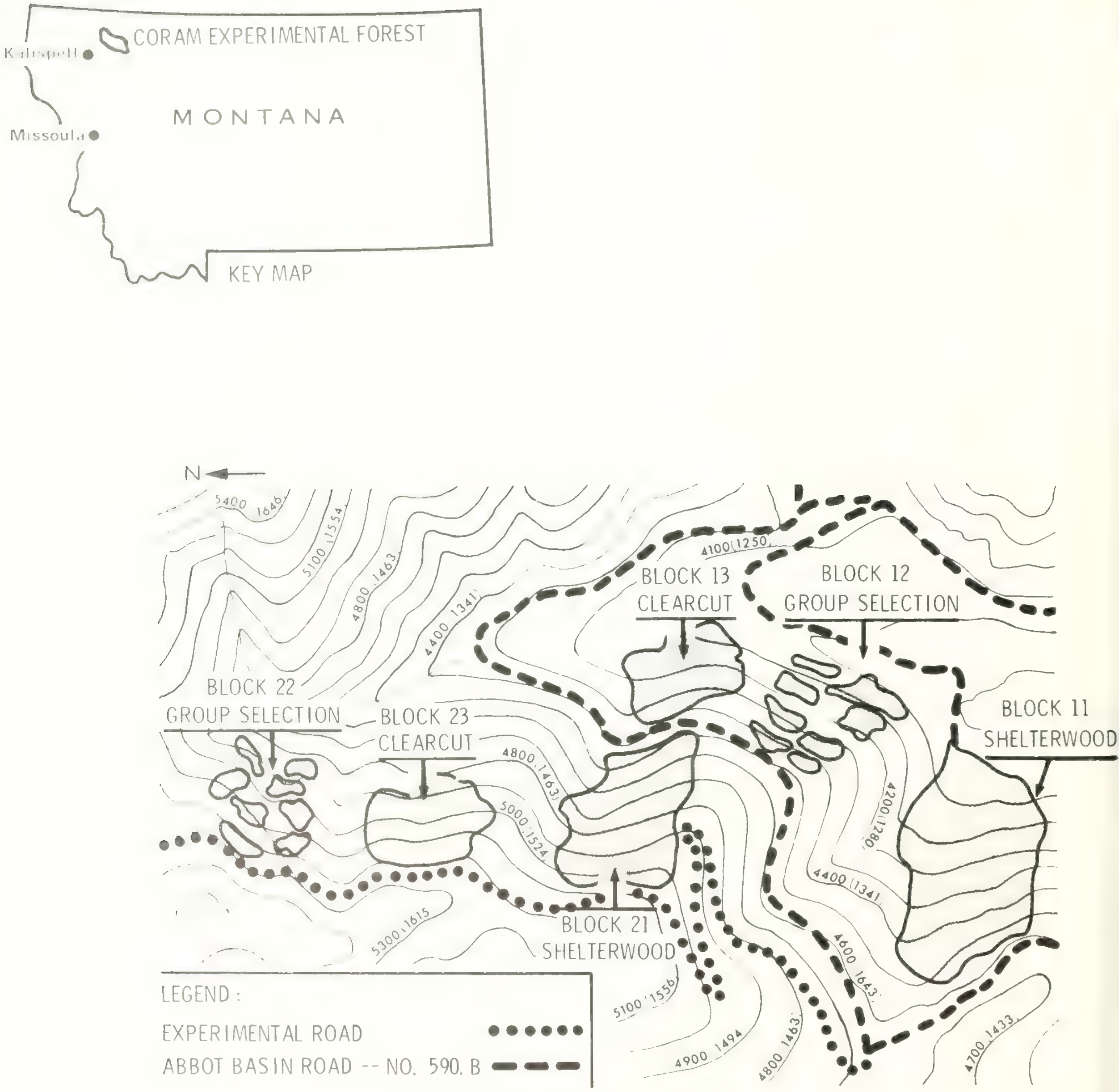

Figure 1.--Location and layout of experimental logging road on Coram Experimental Forest, Montana.

INTRODUCTION

Forest managers face a paradoxical challenge of utilizing forest resources (primarily timber) without damaging or destroying other assets of the forest. Also, with a decreasing land base available for timber growing, more intensive forestry must be practiced in the future. These facts, along the trend toward logging steeper terrain and more fragile soils, increase the potential damage from timber harvesting and road construction. Hence, minimizing the impacts of road construction while still providing for harvesting and traffic needs is essential for continued resource use.

In the past few years, more attention has been given to reducing road impacts, even though some of the trade-offs have not been very well defined. In the past, roads were designed primarily to serve the anticipated traffic needs of the access system. If traffic needs and user costs are the primary consideration, then often the environment suffers. Because so many forest roads must accommodate logging trucks, for safety and economic reasons roads of a higher standard (those incorporating extra width especially) have often been constructed at some expense to some, not well defined to date, environmental and social values.

Information is seriously lacking to evaluate trade-offs related to social, environmental, and economic values associated with different road standards. Because of the paucity of information on which to base decisions, many research projects are now underway or are planned. This paper reports one such study on the Coram Experimental Forest in Montana (fig. 1).

The broad objective of the road study was to locate, design, and construct a road with reduced impacts on the environment that would still serve the near-minimum needs of projected traffic volumes, vehicle sizes, and logging equipment, and to evaluate the costs and impacts. Some of the minimum road design criteria were set by the requirements of the logging and transport equipment. Small commercial running skyline systems were specified to reduce road width requirements as much as possible. This report evaluates road design, construction, and cost and compares costs to those of alternative designs. Also, observations of initial performance of the road and its esthetic acceptability are presented.

ROAD LOCATION AND DESIGN

General Design Procedures

Until the past few years, the environmental and social impacts of road construct were given little or no consideration. Road standards were concerned primarily with geometric and structural features that would provide safe and economical transportati These standards specified some or all of the following:

- --width of road x-section
- --width of clearing
- --grade
- --alinement
- --water control specifications (drainage)
- --consolidation (bearing strength)
- --surfacing.

The principal differences among standards are grade, width, alinement, and surfacing. A so-called low-standard road is often thought to be associated with high environmental impact and a high-standard road with low environmental impact. (Often the results can be opposite to these assumptions.) A road standard, as the term has generally been used, should not be used alone as an indicator of impact--more informa tion about a road is needed to judge impact.

Recognizing the importance of topographical location, proximity to streams, and fragile soils, the environmental and esthetic impacts of roads can usually be minimized by reducing road and clearing widths. Reducing widths accomplishes the followi

- --Reduces the area covered by the road x-section which in turn:
  - --reduces the amount of cut-and-fill slope exposed to view,
  - --intercepts less ground and surface water flow, thereby reducing potential hydrologic impact, and
  - --reduces the potential for erosion.

Other design features that reduce impacts are:

- --fitting the alinement to the topography to avoid large cuts and fills
- --providing adequate drainage for surface and subsurface flow
- --stabilizing subgrades and surfaces
- --stabilizing cut-and-fill slopes by vegetative and mechanical methods.

The guiding criterion for the experimental road was to reduce impacts while stil providing for the basic requirements of the traffic and logging equipment; therefore, width became the most important design feature to reduce exposed area and resulting impacts.

Experimental Road Design

Objectives and Guidelines

The road was constructed to provide access for an experimental logging study of the productivity of skyline logging under different silvicultural and utilization prescriptions. The principal guidelines and constraints were:

--to reduce physical and visual impacts on the site and
--provide access to the harvesting units for all traffic and skyline logging equipment.

Within these guidelines, the major objectives of the study were to:

--develop design criteria to reduce physical and visual impacts and
--assess the environmental impacts and economic performance of the road.

Location and Design

The areas to be harvested and the new road constructed to provide access are shown in figure 1. Three cutting blocks 11, 12, and 13 were accessible from an existing road (Flathead NF road 590-B). The experimental road, an extension of road 590-B, was built to provide access to the other three blocks 21, 22, and 23.

Planning and design for this road proceeded somewhat differently from a normal forest road because of the objectives. However, route reconnaissance and verification proceeded in a normal manner using access needs, available photography, and soils and geologic information. Whenever a skyline logging system is used and access starts from below the units (fig. 1), it is often advantageous to switch back on the terrain to gain the elevation needed for the skyline system. The locations found for the second and third switchbacks, shown in figure 1 and appendix figures 17 and 18, fixed the ruling grade for the primary climbing sections of the road from approximately station 5+00 to 45+00.

After the route was selected, the design phases proceeded differently than for a system road. Because the primary objective was to reduce impacts, especially esthetic impacts, road width was set at the width that would accommodate the tracks of the proposed yarding equipment (12.5 ft (3.81-m)), with a minimum extra width for safety, and a ditch was added for drainage--14-foot (4.27-m) finished surface, with a 3-foot (0.91-m) ditch (app. fig. 19). Normally, a log-hauling cost analysis would be made at this point to assist in determining road width, curve radius, sight distances, and turnout spacing. Instead, the 14-foot (4.27-m) surface was used, and turnouts were placed where the terrain was favorable and are not intervisible as normally desired. As mentioned earlier, landings were not specifically designed, although it was apparent that turnouts and areas where curves were widened could be planned for use as landings.

The following features were specified for the final design.

1. Right-of-way slash was disposed of on the first 59 stations by chipping and scattering. The balance of the slash to station 105+19 was disposed of by burning.

Traditionally, right-of-way slash has been burned. Burning, properly done, not only disposes of the slash, it also immediately returns nutrients to the soil. However, because the area burned is later incorporated in the road, the nutrient return value is questionable. If the job is not done properly, quantities of unburned material usually end up in the road fill. Either way, smoke from burning is objectionable.

An alternative method used for many years for powerline right-of-ways, especiall in gentle terrain, is to chip and scatter the slash. To compare costs and results, this treatment was incorporated.

2. Station 26+00 to 58+00--trees were cut selectively on both cut-and-fill side Removal on cut side as near as possible to cut without danger of slope failure; fill side a minimum of 8 feet (2.44-m) from road shoulder, or the branches trimmed to not interfere with traffic.

Conventional clearing widths have traditionally extended 5 feet (1.52-m) back from the cut slope and minimum of the toe of the fill slope, both depending on soil and timber types and, in some cases, climatic factors. In order to reduce clearing widths to minimize esthetic impacts, the clearing widths were modified as shown.

3. Station 49+00 to 58+00--subsurface conditions allowed for the use of 1/10:1 cut backslopes.

A seismic traverse was run over the entire route to assist in the design of the backslopes. The bedrock in this section was soft enough to rip, (seismic velocity 4,000 ft/sec (1,219 m/sec)), but competent enough to stand on 1/10:1 backslopes. The objective was to reduce the amount of area disturbed by the road prism and the subsequent clearing necessary. Because the exposed rock sections (3/4:1 slopes) on the old road below had not revegetated in 20 years, opening up flatter slopes would appea merely to expose more raw slope to weathering. The steep slopes produce air-slacked material, but so do the flatter slopes.

4. Turnouts were not intervisible.

Turnouts were used when the terrain was favorable, thus keeping road widths down to reduce impacts. Modern logging trucks are equipped with two-way radios that can b used to regulate traffic. This helps compensate for reduced spacing and reduces potential traffic dangers. (This road was closed to public traffic during the study.)

5. Stepped backslopes were used from approximately station 79+09 to 83+53 and were planted to different varieties of shrubs or grass.

Seismic velocities here (station 79+09 to 83+53) showed that the bedrock was com petent to experiment with the stepped backslopes shown in appendix figure 19. When good fill or surface material is needed in a road and, for reasons of overall economy it can be obtained from a cut slope in a favorable location, then some treatment to dampen the appearance of the cut should be utilized. Shrubs were planted in this section to evaluate this treatment.

6. Other selected 3/4:1 backslopes were planted to shrubs or grass.

Revegetation success on road cut slopes steeper than 1:1 has not been good in mo areas of the United States. The reasons are usually instability from air slacking or sloughing, and sometimes lack of moisture because of exposure (aspect). Grass seedin was carefully done with and without a mulch and shrubs were planted to test the cost and effectiveness on some selected slopes steeper than 1:1.

7. Selected fill sections were straw mulched and rolled with an Angeles NF-designed, sheep's foot-type roller to impregnate the straw and stabilize the surface the fill slope.

One of the most effective ways to stabilize steep, granular fill slopes is by impregnating straw with a special roller. The straw does not blow or wash off the sl and the roller compacts the top 6 to 8 inches (15-20 cm) of loose soil on the slope.

8. Neoprene downspouts were used because of better stability on the fill slopes and ability to dissipate part of the energy at the outflow.

Although neoprene downspouts have been used quite often in the past few years, there is still a need for more testing, especially for functioning in different situations and for more information about the life of these structures. Because they do not require anchoring on the slope or connecting bands, they are not likely to be displaced.

Design criteria produced a road shown in the following descriptions and table 1.

--Length - 2.046 miles (3.292 km).
--Width - 14 feet (4.27 m) with 3-foot (0.91 m) ditch--turnouts were combined with probable logging set locations; standard curve widening.
--Maximum grade - 9.41 percent; average grade - 6.72 percent.
--Minimum curve radius - 75 feet (22.9 m).
--Surfacing - none.
--Standard clearing width - 5 feet (1.52 m) from cut slopes and toe of fill.
--Clearing from station 26+00 to 58+00 - trees cut selectively on both cut-and-fill sides--removed on cut side as near as possible without danger of slope failure; fill side a minimum of 8 feet (2.44 m) from road shoulder, or the branches trimmed to not interfere with traffic.
--Culverts - 18-inch (0.457-m) C.M.P. minimum size.
--Downspouts - flexible neoprene.
--Compaction - with grading equipment.

Table 1.--*Grade, distance, and alinement--experimental section Abbot Basin Road 590-*

Section		Station	Grade	Distance		No. curves	Curve radius
		100 ft					*Degrees*
I	1	0-2+00	3.85	0.038	(.061)	[illegible]	
	2	2+00-5+00	6.60	.057	[illegible]	[illegible]	108, [illegible]
	3	5+00-7+00	4.65	.038	[illegible]	0	
	4	7+00-16+60	8.82	.182	293	[illegible]	[illegible]
	5	16+60-21+00	8.64	.083	.134	[illegible]	143, 143
	6	21+00-25+00	6.84	.076	.122	0	
	7	[1]22+14-26+50	9.12	.083	.134	2	286, 358
	8	26+50-30+50	5.25	.076	[illegible]	2	88, [illegible]
	9	30+50-36+00	8.22	.104	.167	3	[illegible], [illegible], 358
	10	36+00-42+55	7.53	.124	.200	4	[illegible], 204, 179, 358
	11	42+55-48+00	3.85	[illegible]	.166	[illegible]	75, [illegible]
	12	48+00-56+00	[illegible]	.152	.245	[illegible]	358, 358, [illegible]
	13	56+00-59+40	9.41	.064	[illegible]	1	[illegible]
II	14	59+40-65+50	6.19	.112	[illegible]	2	[illegible], 179
	15	65+50-70+50	4.45	.095	.153	1	[illegible]
	16	70+50-74+50	7.62	.076	[illegible]	2	[illegible], 140
	17	74+50-85+00	5.63	.199	.320	3	477, 573, [illegible]
	18	85+00-91+00	[illegible]	.114	.183		[illegible], 143, 143
	19	91+50-94+65	6.58	.069	.111	1	[illegible]
	20	94+65-99+00	1.38	.082	132	1	[illegible]

[1] Equation:

For analysis purposes (used later), the road was divided into two [illegible] climbing and switchback 0+00-59+40 and 59+40-99+00.

	Ave. grade	Ave. curve radius	No. curves/mile(/km)
Section I	7.26%	229	[illegible] ([illegible])
Section II	5.90%	297	17.4 (10.8)

ALTERNATIVE DESIGNS, CONSTRUCTION, AND COSTS

Alternate Designs and Construction Cost

To evaluate the probable effects of alternative designs, the study road P-Line location is retained and adjustments for different standards made from the P-Line. (The P-Line, or route location, is of prime importance no matter what width or other parameter adjustments are made to the final design. Often it is impossible for design changes and innovations to compensate for inadequate route selection.) Because of the relatively small central angles for most curves on the design road, except the switchbacks, and because of the minimum curve radius of 75 feet (22.9 m), the primary adjustments made for two simulated road standards (an SN-16 (4.88) and a DN-24 (7.32)) were in road and clearing widths. The designations for road standards in the Forest Service are being revised. In the old system, SN-16 (4.88) designates a single-lane, normal 16-foot-wide (4.88 m) road. In the new nomenclature, the numbers following the letter designations represent design speed. For example, S-15 (24.1) designates a single-lane, road designed for a speed of 15 miles per hour (24.1 km/h). The latter designation is more descriptive of the trafficability, but doesn't give specific information about width. However, often because of curve widening, width added for settling and slough, and turnouts, width of a single-lane road varies so much that very few sections end up design-template width, anyway. Both designations for standard will be shown, with the design speed designation in parentheses.

For comparison, the side-by-side quantities and cost will be shown for each case or standard below:

I. SN-14 (4.27) (S-15 (24.1)) - 3-foot (0.91-m) ditch (the experimental road).

II. SN-14 (4.27) (S-15 (24.1)) - 3-foot (0.91-m) ditch without backslope or clearing modifications; that is, 3/4:1 backslopes throughout, standard clearing widths.

III. SN-16 (4.88) (S-17 (27.4))[1/] - 3-foot (0.91-m) ditch with the same backslope and clearing modifications as the experimental road.

IV. DN-24 (7.32) (D-24 (38.6)) - 4-foot (1.22-m) ditch with the same backslope and clearing modifications as the experimental road.

The design quantities were computed using the computer program of the Northern Region, Missoula, Montana. Table 2 shows the construction items and cost for each of the above standards.

[1/] Normally a road would not be designed for a speed of 17-mi/h (27.4-km/h)--in this case, the 16-foot-wide (4.88-m) road with turnouts provides a facility for 17-mi/h (27.4-km/h) traffic.

Table 2.--Construction items, unit cost, [illegible] alternative road standards (Dollars)

Construction item	Unit of measure	Unit cost	Alternative road standard							
			I		II		III		IV	
			Units	Cost	Units	Cost	Units	Cost	Units	Cost
Clearing and grubbing (chipping)	hectare (acre)	4,568.00 (1,850.00)	3.24 (8.00)	14,800	3.44 (8.50)	15,725	3.50 (8.65)	[illegible]	4.[illegible] (10.[illegible])	[illegible]
Clearing and grubbing (burning)	hectare (acre)	3,951.00 (1,600.00)	2.54 (6.27)	10,032	2.57 (6.34)	10,141	[illegible] ([illegible])	10,[illegible]	3.50 (8.63)	13,803
Unclassified excavation (Std. I, II, and III)	meters^3 (yards^3)	1.63 (1.25)	34,773 (45,483)	56,854	36,664 (47,957)	59,946	37,948 (49,636)	62,045		
Std. IV		1.25 (0.96)							59,086 (77,284)	74,193
Slope Rounding	(linear) meters (feet)	0.11 (0.35)	744 (2,440)	854	744 (2,440)	854	744 (2,440)	854	744 (2,440)	854
Overhaul	m^3 km (yd^3 mi)	2.63 (1.25)	82.3 (173.3)	217	159.8 (336.4)	420	148.9 (313.4)	[illegible]	205.5 (432.6)	[illegible]
Corrugated metal pipe-4.57 m (18 in) dia.	(linear) meters (feet)	26.30 (8.00)	152 (500)	4,000	152 (500)	4,000	177 (580)	4,640	211 (691)	5,528
Total cost	$			86,757		91,089		94,[illegible]		114,481
Cost per km (mile) for 3.29 km (2.046 mi)	$/km			26,370 (42,403)		27,686 (44,520)		28,804 (46,317)		34,797 ([illegible])

It is readily apparent from table 2 that using 1/10:1 backslopes, where subsurface conditions were favorable, and reducing clearing widths, saved cost ($4,333) and reduced impact with no adverse effects on logging or hauling cost.

The cost of a conventional road can be estimated from table 2 by using standard clearing and grubbing cost ($1,600/acre ($3,951/ha)) for these quantities for road standard II. The estimated cost for a conventional road then is $88,965 vs $86,756 for the experimental road.

User Cost

The differences in construction cost show the additional capital investment required for higher standard roads. One must also compare effects of standards on user cost. For most forest roads, timber hauling cost is the major user cost.

As normal planning procedure, these costs are used to compare the potential benefits with the impacts they create to assist in determining road standards. A volume of traffic of 10 vehicles per hour is assumed for the computation of minutes per round trip mile (kilometer) in tables 3, 4, and 5. This was done to make the comparison for traffic volumes more typical of a system road in this area. The Logging Road Handbook, Byrne and others (1960) was used for the computation.

Tables 3, 4, and 5 show that when a road is laid lightly on the land (contoured), the alinement will usually control the speed, when ruling grades are less than 6 to 7 percent. This means that any significant improvement in speed (reducing vehicle user cost) must be gained by increasing width, as was done in this case.

Under the assumptions used for table 6, 12,936 M bd. ft. (51,223 m^3) of timber would be carried over the road annually. Although 10 VPH is relatively light traffic when a substantial part of the traffic is logging trucks, 50 percent in this case, a rather large volume of timber could be transported each year. As traffic increases, especially logging traffic, users tend to favor higher standards because of lower costs (Gardner 1971).

Table 3.--*Minutes per round trip mile (km) - SN-14 (4.27) (S-15 (24.1))*

Road section[1]	Grade		Alinement	
	Loaded	Empty	Loaded	Empty
I	2.55 (1.58)	2.25 (1.40)	4.00 (2.49)	3.90 (2.42)
II	2.20 (1.37)	1.90 (1.18)	3.50 (2.18)	3.50 (2.18)

	Time gov. by empty[2]	Total time RTM (RTKm)	Distance RT	Time/section
I	4.13 (2.57)	8.13 (5.05)	2.26 (1.40)	18.37 (11.42)
II	3.80 (2.36)	7.30 (4.54)	11.49 (0.93)	10.83 (6.73)

[1] Road sections are used to facilitate the hauling analysis as shown in table 1.

[2] Increase dependent on spacing of turnouts.

Total time RTM = 18.37 + 10.83 = 29.20 min
Total time RTKm = (11.42) + (6.73) = (18.15) min
Weighted average for both sections = 7.79 min/RTM (4.84 min/RTKm) (15.4 mi/h (24.8 km/h))

Table 4.--*Minutes per round trip mile* [illegible]

Road section	Grade		Alinement	
	Loaded	Empty	Loaded	Empty
I	2.55 (1.58)	2.25 (1.40)	3.70 (2.30)	3.50 (2.18)
II	2.20 (1.37)	1.90 (1.18)	3.40 (2.11)	3.20 (1.99)

	Governing time	Total time RTM (RTKm)	Distance RT	Time/section
I	3.71 (2.31)	7.41 (4.61)	2.26 (1.40)	16.75 (10.41)
II	3.47 (2.16)	6.87 (4.27)	1.49 (0.93)	10.24 (6.36)

NOTE: Total time RTM = 16.75 + 10.24 = 26.99 min
Total time RTKm = (10.41) + (6.36 = (16.77) min
Weighted average for both sections = 7.20 min/RTM (4.52 min/RTKm) (16.7 mi/h (26.9 km/h))

Table 5.--*Minutes per round trip mile (km) - DN-24 (7.32) (D-24 (38.6))*

Road section	Grade		Alinement	
	Loaded	Empty	Loaded	Empty
I	2.55 (1.58)	2.25 (1.40)	2.60 (1.62)	2.60 (1.62)
II	2.20 (1.37)	1.90 (1.18)	2.30 (1.43)	2.30 (1.43)

	Governing time	Total time RTM (RTKm)	Distance RT	Time/section
I	2.60 (1.62)	5.20 (3.23)	2.26 (1.40)	11.75 (7.30)
II	2.30 (1.43)	4.60 (2.86)	1.49 (0.93)	6.85 (4.26)

Note: Total time RTM = 11.75 + 6.85 = 18.60 min
Total time RTKm = (7.30) + (4.26) = (11.56) min
Weighted average for both sections = 4.96 min/RTM (3.08 min/RTKm) (24.1 mi/h (38.8 km/h))

For the cost comparisons in tables 6 and 7, the following assumptions were made:

Table 6

--10 vehicles per hour (VPH)--with half of the traffic logging trucks and half administrative and other traffic.
--cost of operating logging trucks, including the drivers' wages--0.25/min.
--cost of operating other vehicles--0.04/min.
--8-hour hauling day, 140 days per year use.
--20-year road life.
--6 percent interest.
--6.0 M bd. ft. (23.8 m^3) loads for logging trucks.

Table 7

--5 VPH--half logging, half other.
--all other assumptions same as table 6, except
--average load of logging and residue trucks used from Coram experimental logging study--3.84 M bd. ft. (15.2 m^3).

Table 6.--*Cost summary comparison (10 VPH--1/2 logging trucks, 1/2 other traffic)*

Road standard	Annual amortized diff. in cost[1]	Annual diff. hauling cost	Annual diff. other traffic	Net diff.
	- - - - - - - - - - - - - - - - - -	*Dollars*	- - - - - - - - - - - - - - - - - -	
I	0			
III	+ 1,842.99	- 6,209.28	- 862.40	- 5,228.64
IV	+11,790.22	-30,529.96	-4,743.20	-23,482.94

[1] Capital recovery--6%, 20-year life.

Table 7.--*Cost summary comparison (5 VPH--1/2 logging trucks, 1/2 other traffic)*

Road standard	Annual amortized diff. in cost	Annual diff. hauling cost	Annual diff. other traffic	Net diff.
	------------------------------	*Dollars*	------------------------------	
I	0			
III	+ 1,842.99	- 3,187.65	- 431.20	-1,775.86
IV	+11,790.22	-15,287.59	-2,371.60	-5,868.97

The data in table 7 more nearly approximate the traffic volume for the experiment sale (presently a dead end road), although the traffic was more intermittent and did not extend for a full 140 days during the year of the logging (1973).

Table 7 also indicates that this volume of traffic is near the break even point for road standards (primarily width in this case) related to hauling cost. For this particular road, just wide enough for the logging equipment, any environmental values obtained would cause little economic sacrifice. (For the Coram experimental sale, onl about 1 1/2 million board feet (5,535 m^3) were harvested).

The preceding discussion and comparisons would be useful for deciding road standards. To complete an analysis of road standards, the effect of the road standard on harvesting cost as well as hauling cost would be necessary. However, the effects on harvesting cost could not be made for this study where only one standard was built.

ROAD PERFORMANCE TO DATE

Structural Features

Road inspections of April and June of 1974 and observations throughout the summer and fall of 1974 showed no structural failures of any kind. Some minor sloughing and settling had occurred.

1/10:1 backslopes.--Two photos taken from approximately station 54+00, after the first winter and after final grading, tell the story. Figure 2 shows two or three sections where 1/2 to 1 cubic yard (0.13-0.26 m^3) of rock sloughed off the cut bank. Figure 3 shows the same section of road after final grading and how it appeared the balance of the year. Only minor sloughing is likely in the future.

3/4:1 backslopes.--Two areas of 3/4:1 backslopes showed some sloughing or slumping after the first winter, but are now relatively stable and no major failures are anticipated. Figure 4 shows minor slumping at station 37+20 on a relatively long slope in the deepest soil mantle found on the entire road. Some minor sloughing or slumping could be expected on 3/4:1 backslopes in this material.

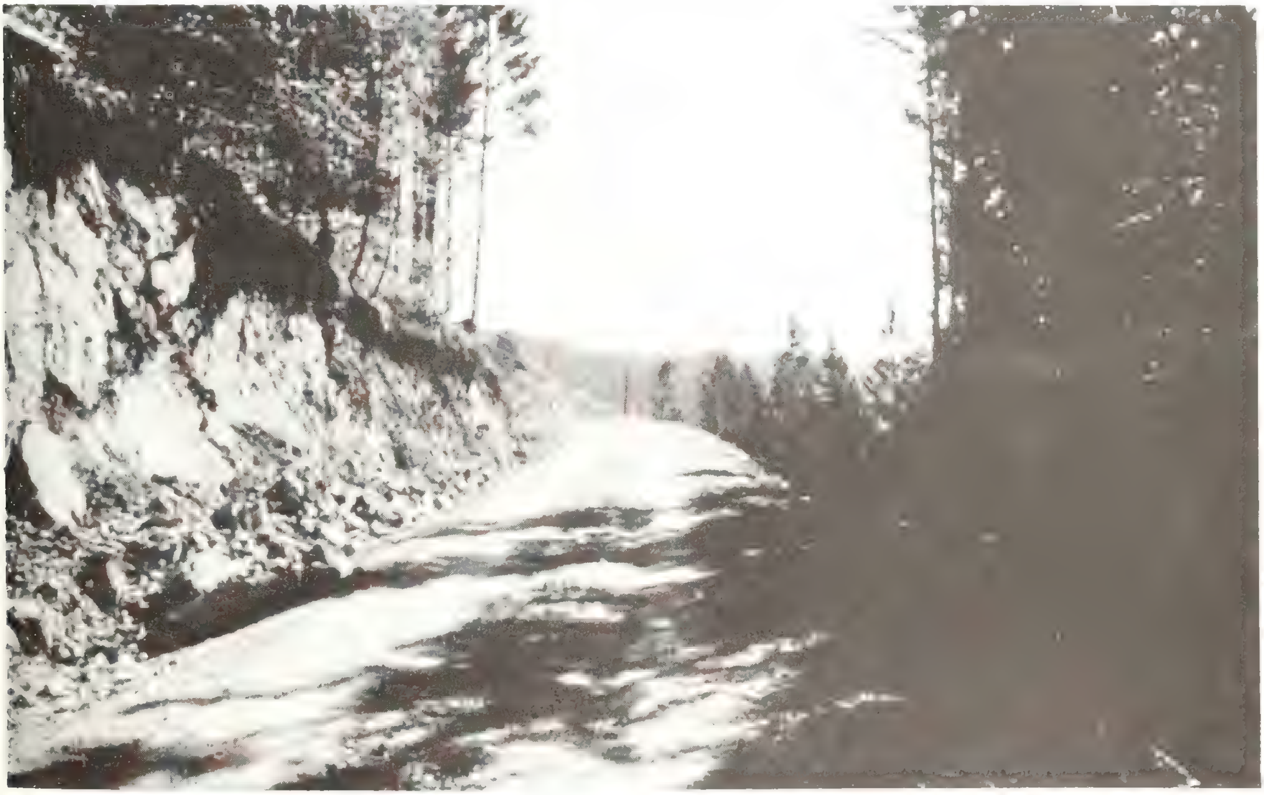

Figure 2.--Near station 54+00--view of 1/10:1 backslopes before final grading.

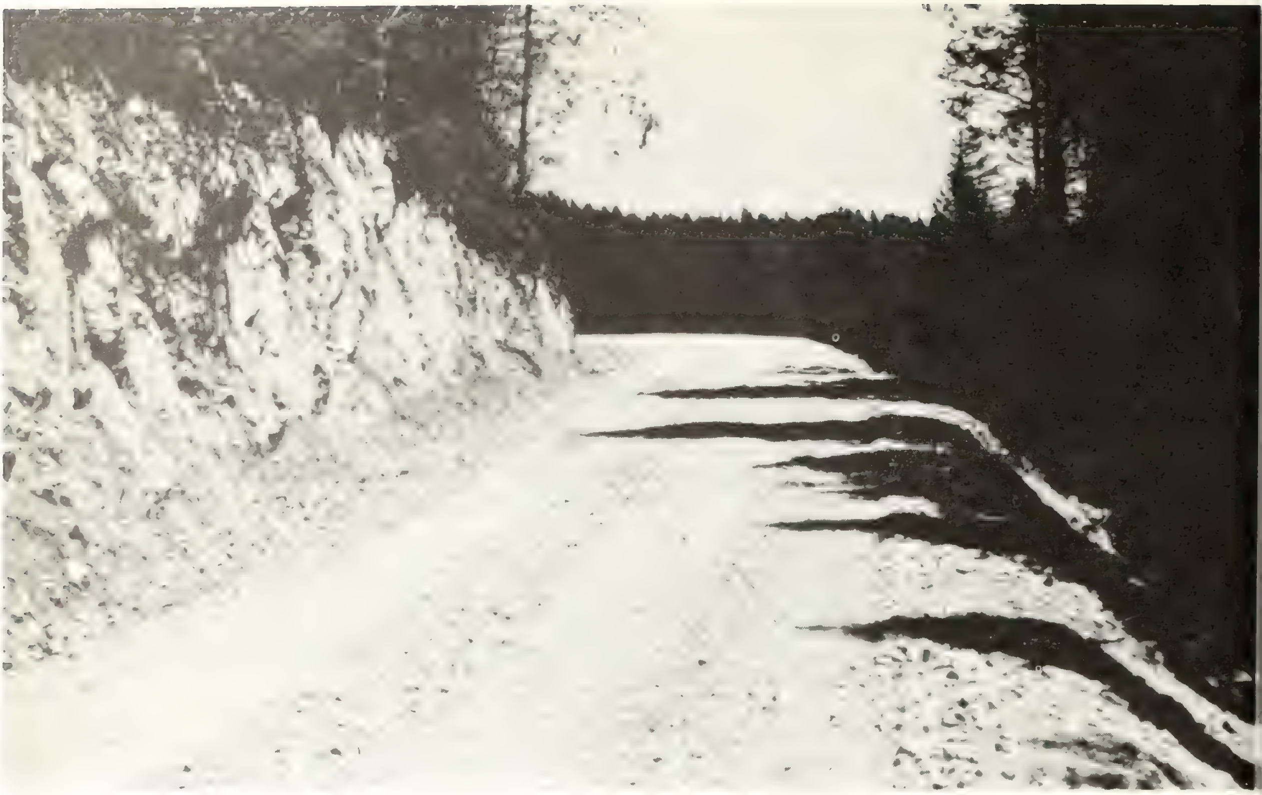

Figure 3.--Near station 54+00--view 1/10:1 backslopes after final grading.

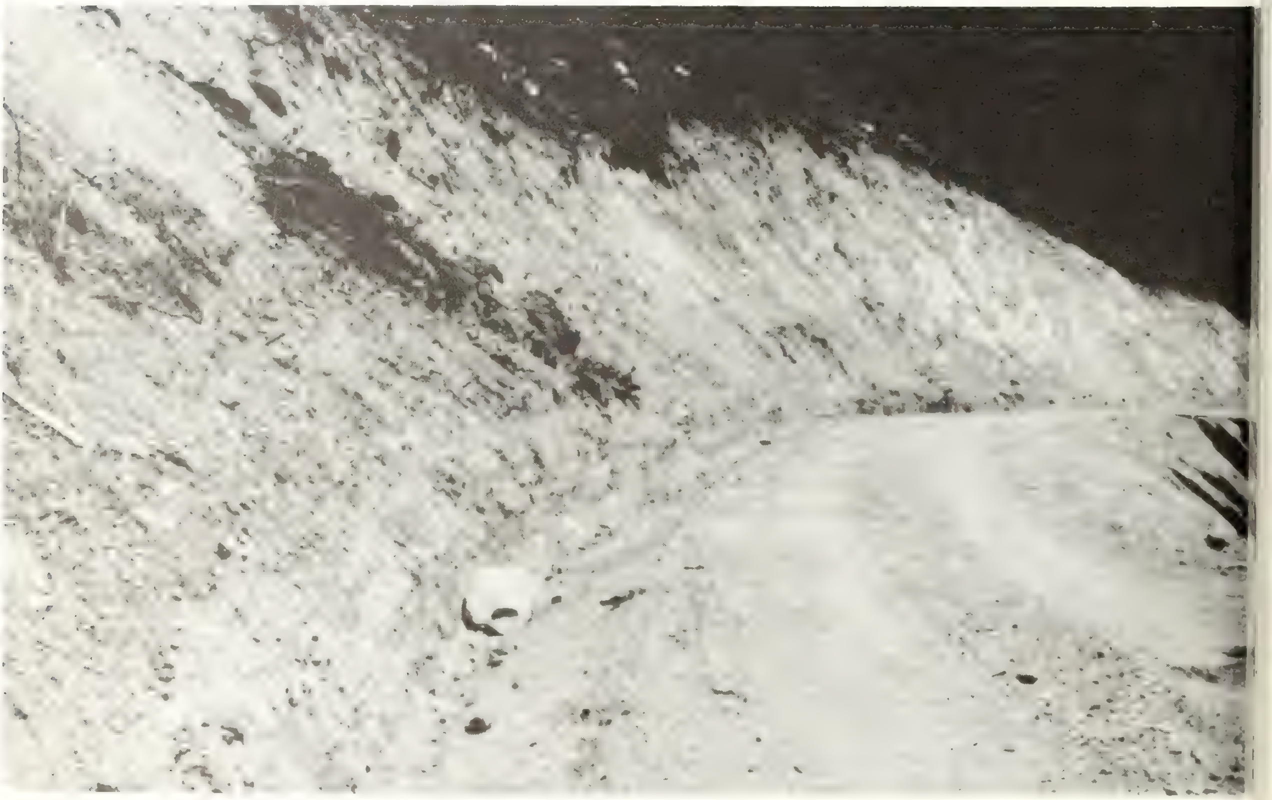

Figure 4.--Slumping cut slope near station 37+20.

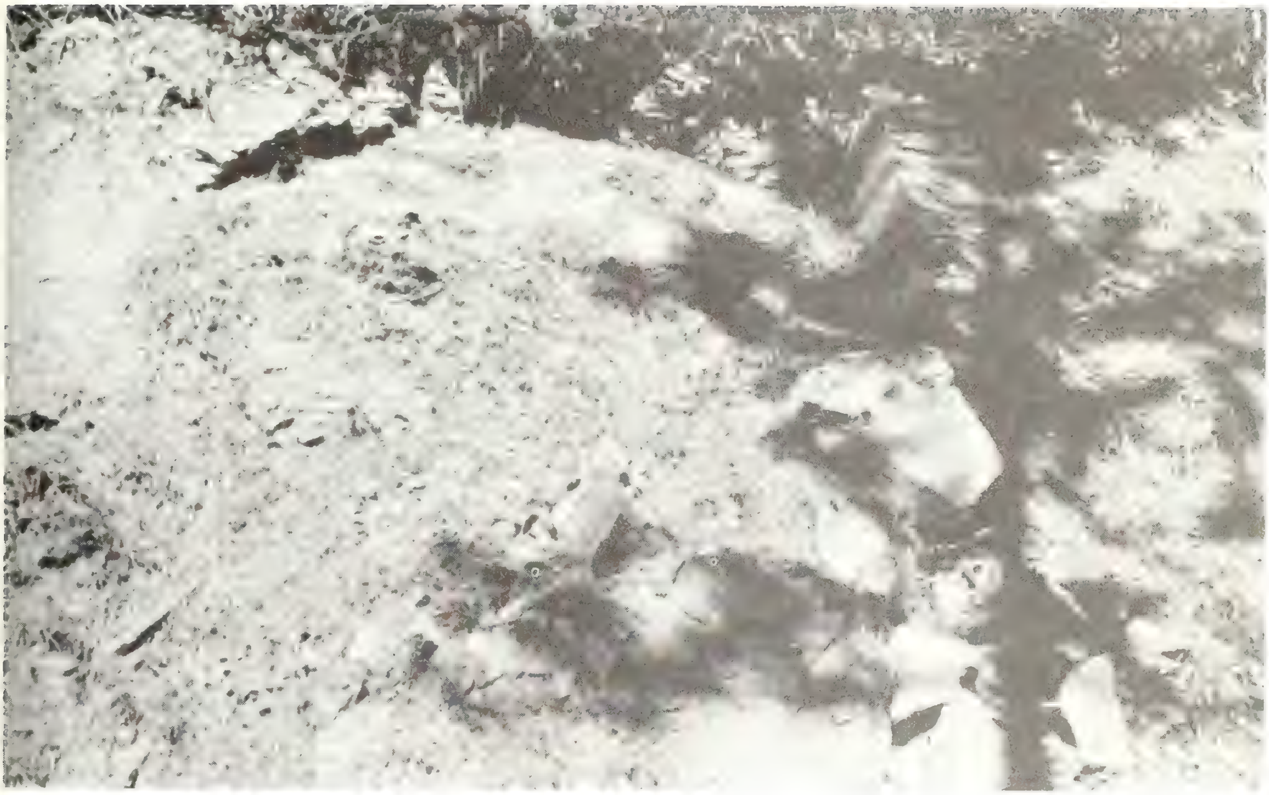

Figure 5.--Minor settlement in rock fracture at station 64+34.

A minor U-shaped settlement occurred in the cut bank at station 64+34 (fig. 5) because of rock fracturing.

In figure 6, several yards of rock slabbed off the cut bank at station 76+20 because of dip and fracture in the bedrock. No further sloughing of any extent is expected here.

Stepped or serrated backslopes.--An experimental section of approximately 450 feet (137 m) of backslope was stepped to test growth of grass and shrubs and to evaluate esthetics and stability. This area has relatively high precipitation and a favorable aspect. Revegetation success was generally good. Figure 7 shows a completed section of serrated backslope. The dip and strike of the rock formations made stepping difficult and resulted in the steps being not quite as wide as planned. The steps have been planted, and it is believed that most of the sloughing expected has taken place. Sloughing eventually leaves less pronounced steps, but provides a seedbed and more moisture to the plants.

Fill slopes.--Fills were designed on either a 1 1/2:1 or 1 1/4:1 slope, depending on the material. Many sections contained enough rock to support 1 1/4:1 slopes. Fill slopes were compacted by the earth moving equipment. Figure 8 shows a typical fill at station 87+75. The material in the area of station 93+00 produced the only section where the fill slope was slightly undulating, shown in figure 9.

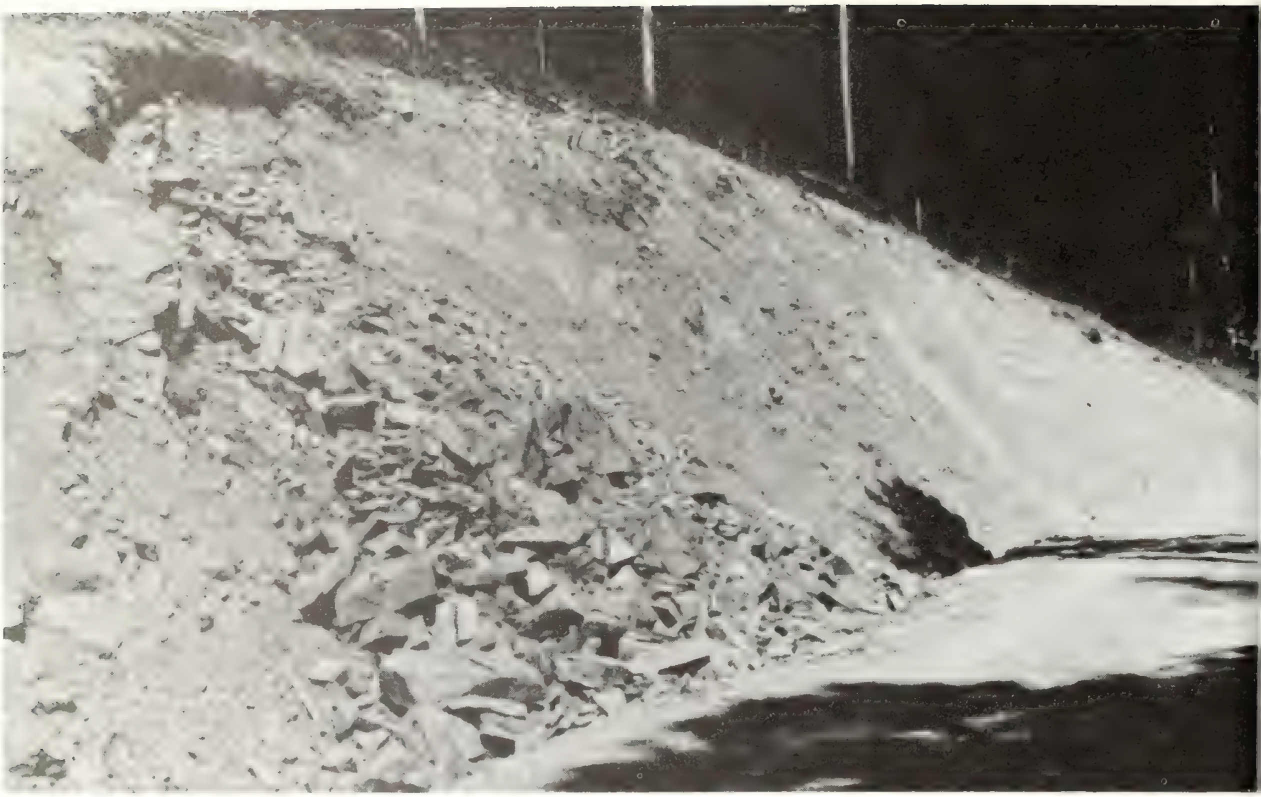

Figure 6.--Rock slab spalling due to dip and fracture at station 76+20.

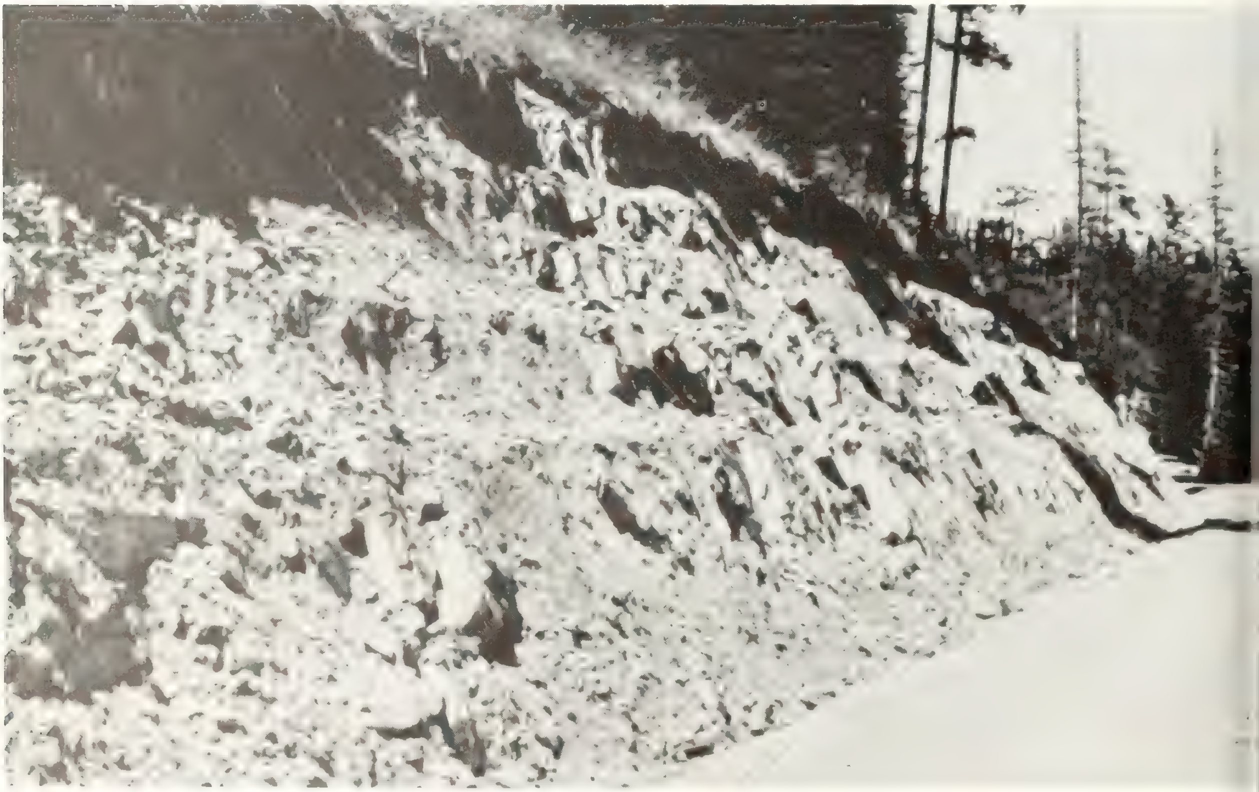

Figure 7.--Stepped backslopes in rock cut near station 82+50.

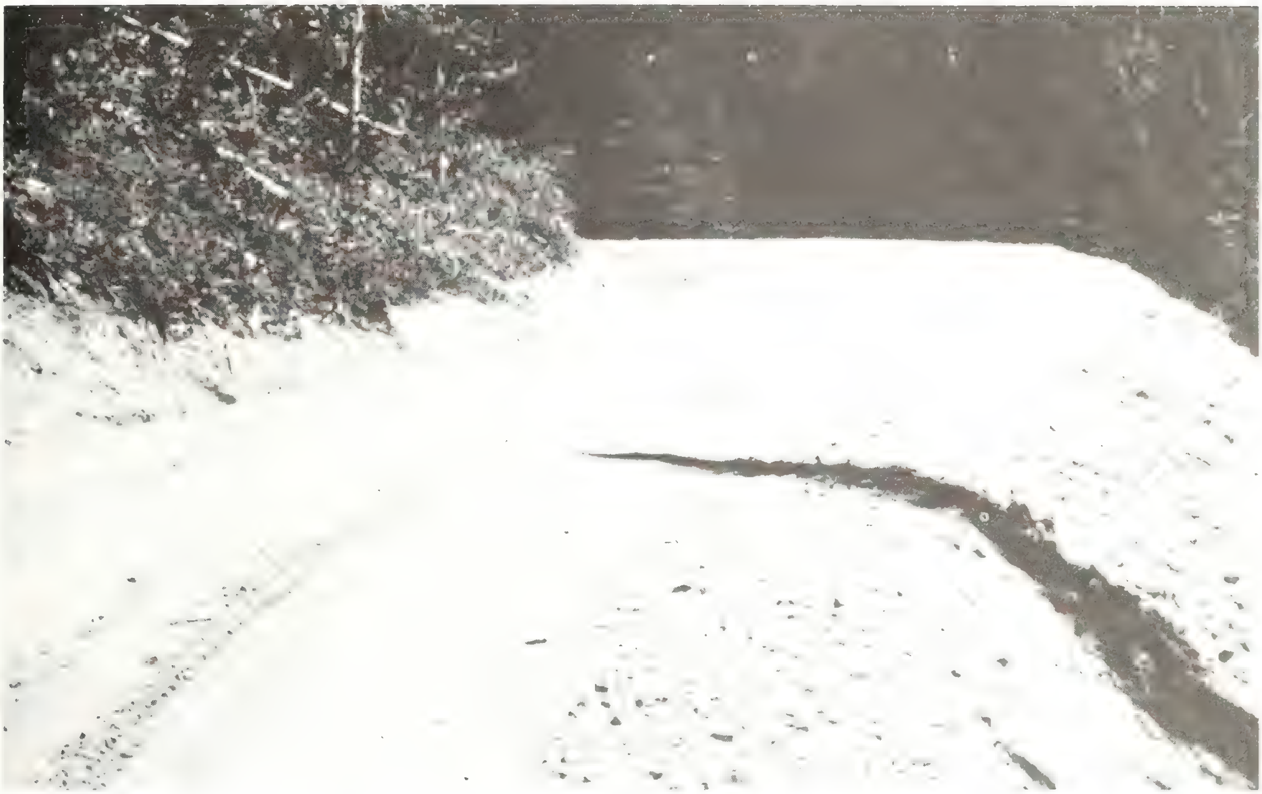

Figure 8.--Typical side-cast fill on 1 1/2:1 slope at station 87+75.

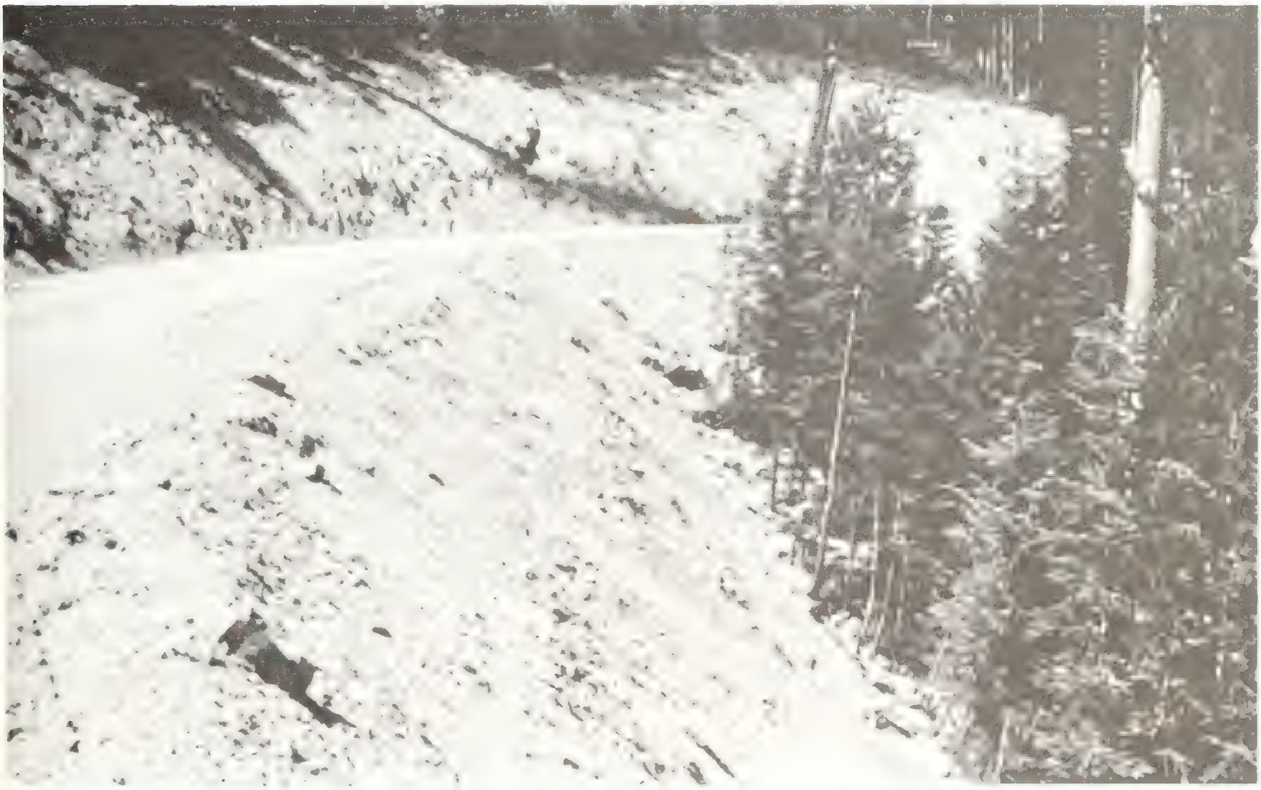

Figure 9.--Fill containing some fine colloidal material that produced a slightly uneven but stable slope at station 93+00.

Drainage

Drainage is provided by a 3-foot (0.91-m) ditch, corrugated metal pipe, and neoprene downspouts. Only three culverts experienced any flow during the first year. However, seasoning of the ditch sections will produce more flow in the future.

Minor seepage was recorded in April from four cut bank sections at stations 12+40, 21+75, 41+00, and 55+00. The seepage at the first two locations continued throughout the year, but no damage resulted from the seepage. A typical area of seepage is station 41+00, shown in figure 10.

Neoprene downspouts were used because of their greater stability on fill slopes and effectiveness in dissipating part of the energy under conditions of flow. The installation at station 57+50 is shown in figure 11.

Porous soil over the fractured limestone basin minimized the need for water control.

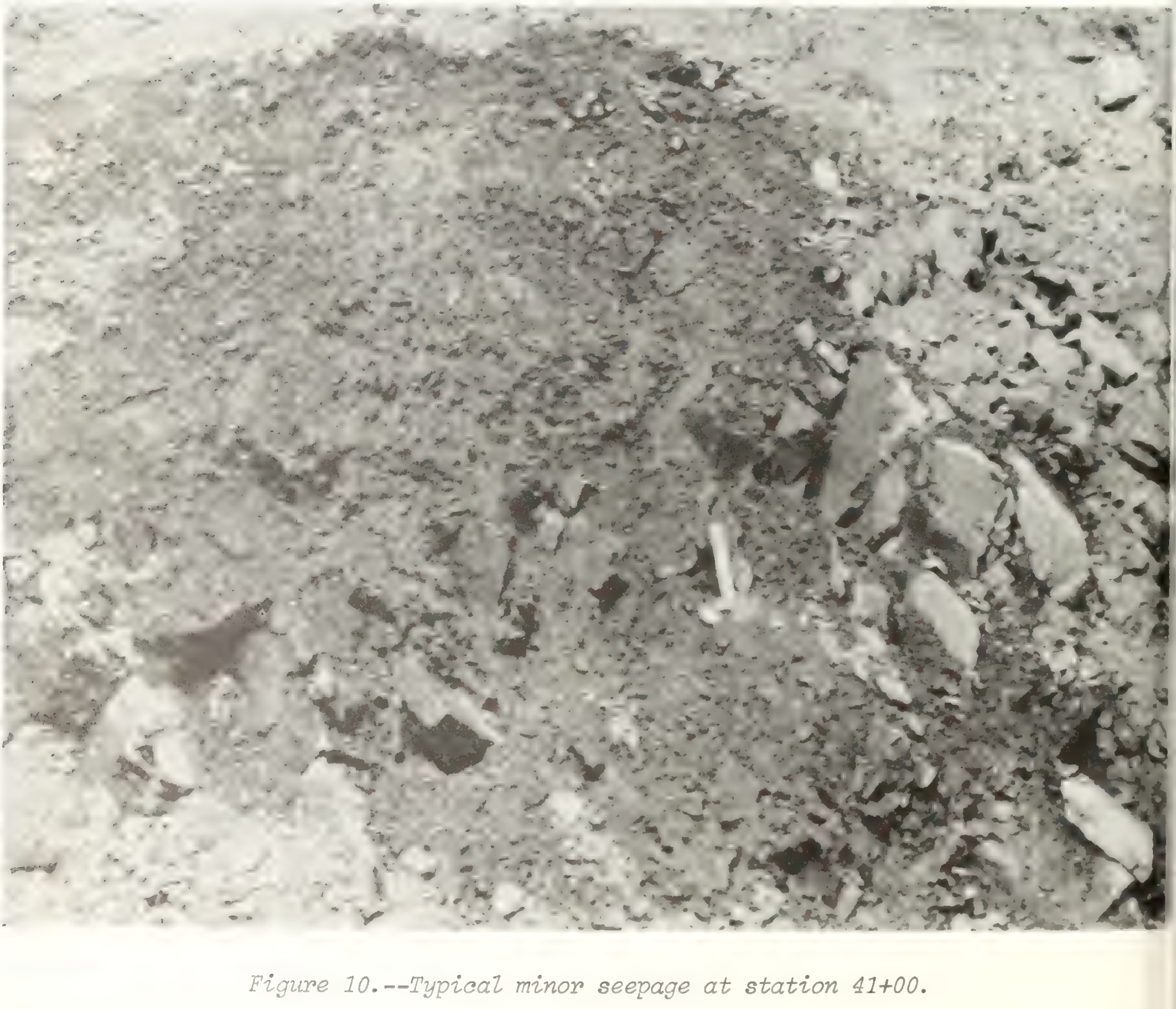

Figure 10.--Typical minor seepage at station 41+00.

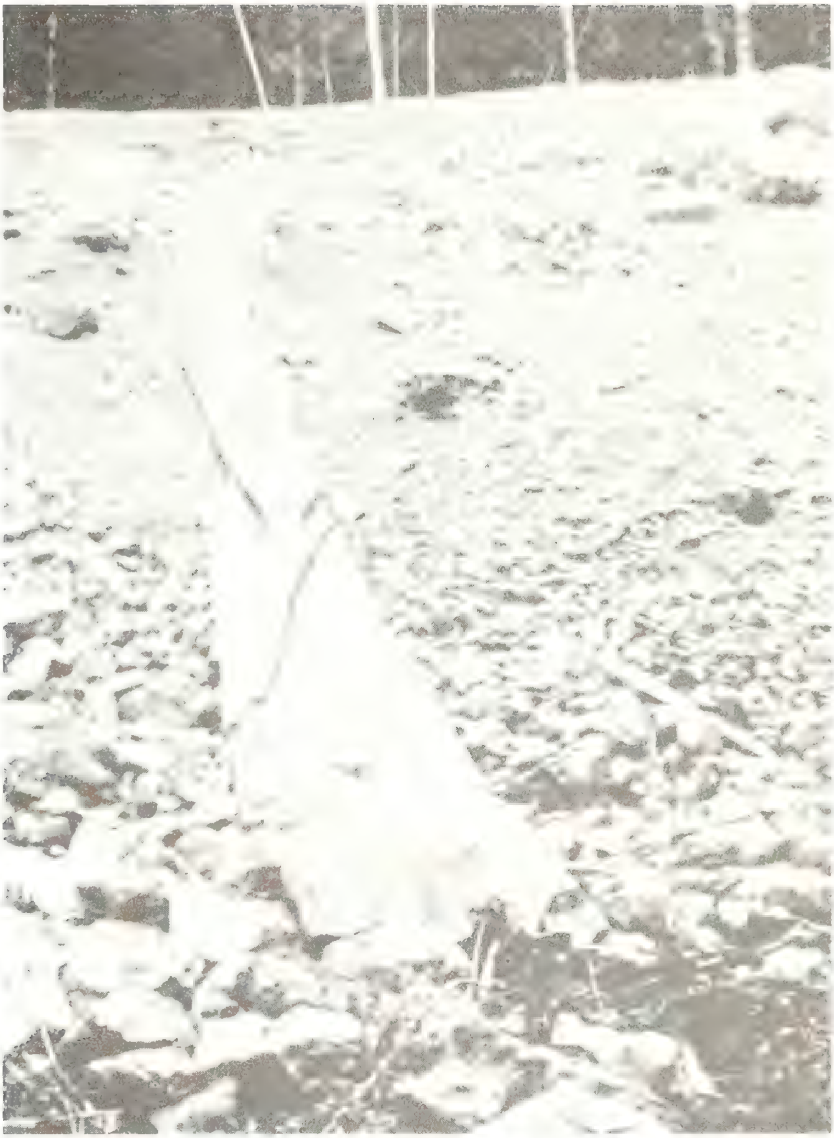

Figure 11.--Neoprene downspout laid on top of fill at station 57+50.

Clearing

Slash from the road right-of-way was disposed of on the first 59 stations by chipping and scattering. Because of this requirement, the contractor removed and sold much more small material than he would have on a pile-and-burn operation. This resulted in very small volumes of material being chipped and scattered. The author couldn't find a concentration of chips visible enough to photograph! Only the tops and limbs, in most cases, were chipped in a small Fitchburg right-of-way chipper.

The difference in overall appearance between the standard and reduced clearing widths can be seen in figures 12 and 13. As previously discussed, reduced clearing widths generally reduce esthetic impacts.

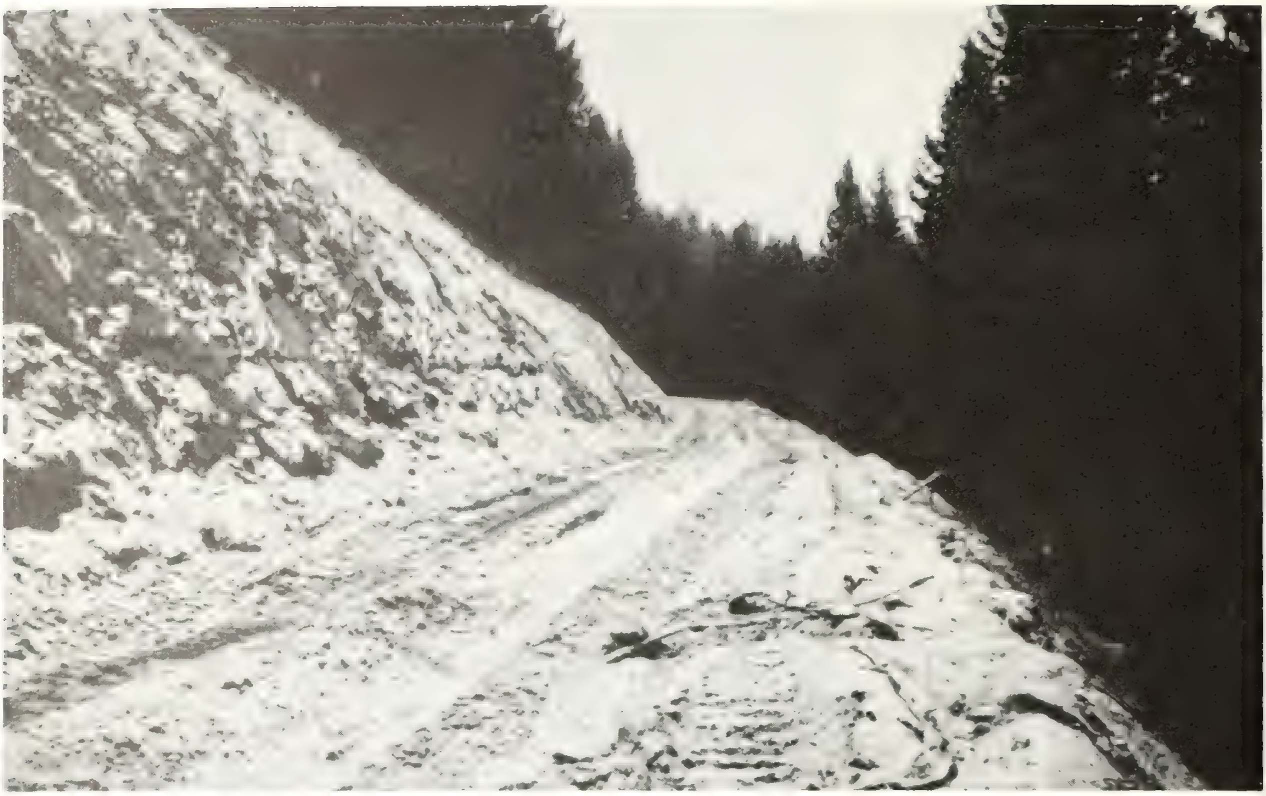

Figure 12.--Road section, conventional clearing.

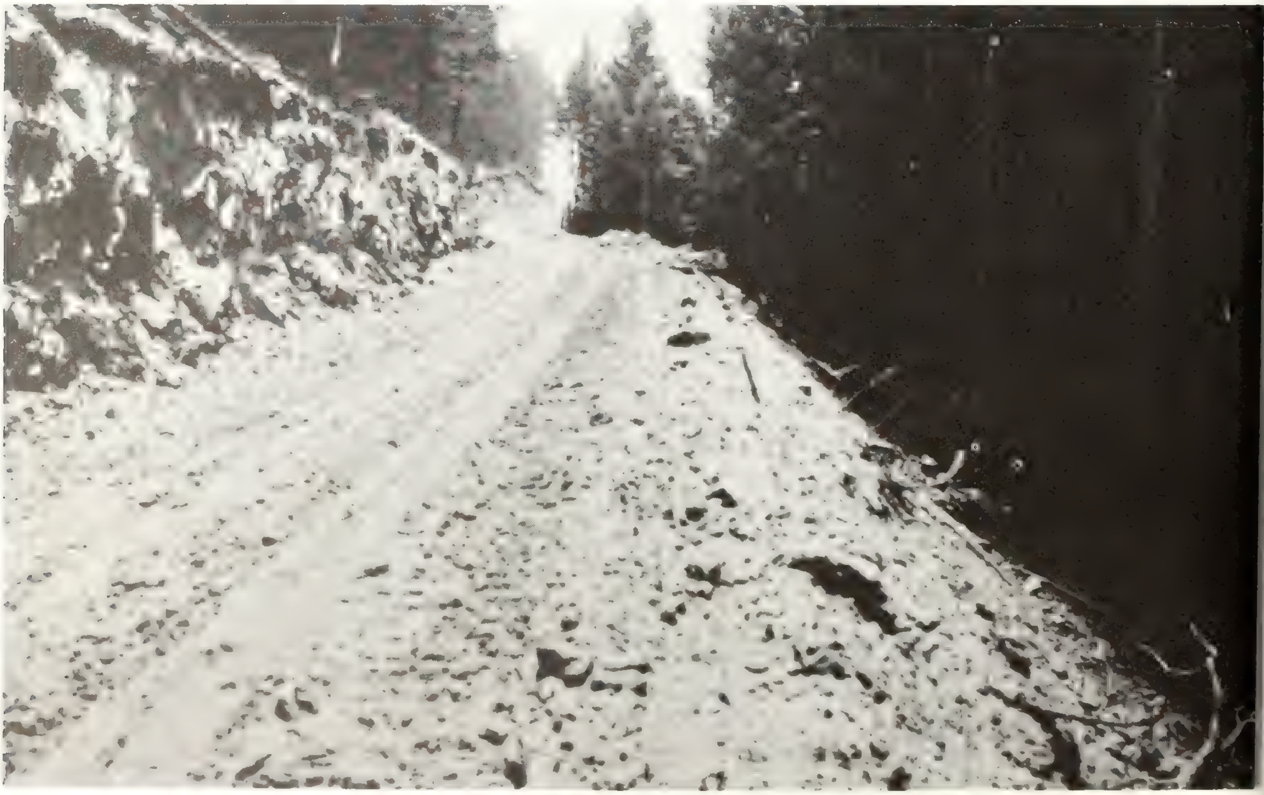

Figure 13.--Road section with vertical cut and reduced clearing width.

Erosion

Runoff and erosion were not anticipated to cause significant problems because of the leaky, fractured limestone basin and the road material. There was no evidence of overland flow on the location before the road was constructed, and very little subsurface flow has been intercepted by the road prism. Obviously, the percolation rate is high and the phreatic gradient steep.

The first year after construction, ditch flow was small and carried little or no sediment. No evidence of overland flow of sediment was found and little or no sediment is expected. The entire section of road is separated from any live stream. Hence, if in the future any sediment flow does develop, it would not reach a live stream.

Revegetation

Because the revegetation experiments will be reported in detail in another paper, only the generalities will be discussed here. The primary objectives of revegetation were to help stabilize the slopes and reduce visual impact. The relative importance of these objectives for any road varies with the location of the road. Location affects stability and visual considerations. For example, in some cases, revegetation could be entirely for esthetic reasons.

The shrubs and grass used for revegetation were listed in appendix tables 8 and 9, along with the first-year survival on the shrubs. Obviously, the effect of these plantings on the appearance of the road cannot be evaluated until the shrubs have had some time to develop. Initial survival is very good and, since this is the most critical time for survival, good overall results are expected.

Fill slopes that are difficult to revegetate have generally been most successfully treated by applying a mulch held in place by netting or impregnation. The sheep's foot-type roller, designed by the Angeles National Forest (fig. 14), has been proven effective in compacting the top 6 to 8 inches (15-20 cm) of soil, while at the same time impregnating straw mulch well into the soil. The roller was used on several fill sections; results will be reported when data have been analyzed. (The experimental seeding and planting were done by research personnel and were not a part of the road contract.)

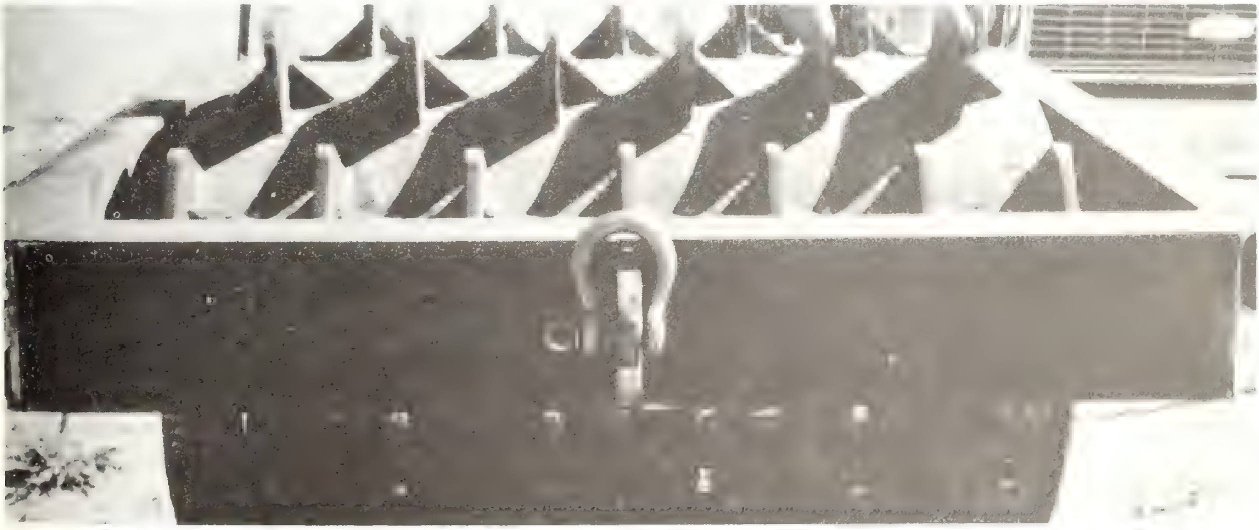

Figure 14.--Angeles N.F. roller-compactor.

Esthetics

As emphasized in this report, esthetics are probably influenced by the width of th road cross-section and clearing more than anything else. (Also, visual impact of the effects of raw cut-and-fill slopes, whatever the road width, is reduced by revegetation

A view of the basin (showing the old road) before clearing for the new road is shown in figure 15; a view after clearing for the new road is shown in figure 16. (Figures 12 and 13 show two sections of the new road, particularly effects of reduced clearing width.)

In figure 15, the clearing and cross section of the old road are prominent in the center of the picture. In figure 16, the same view after the new road was completed, the clearing for the new road is barely visible above the old road. Figure 12 shows a cut-and-fill section using conventional backslopes and clearing specifications. Compar this photo with figure 13 where 1/10:1 backslopes and reduced clearing widths were used (Both photos were taken before final cleanup and grading.)

To minimize miles of road, one must use logging systems that require few roads. The research on the Coram site was to demonstrate the effects of logging systems that require fewer miles of road and produce less impact than conventional methods. Instead of the traditional Idaho jammer that required road spacings of 300-600 feet, (91-182 m) a skyline system was selected that had the potential to increase road spacing to about 2,000 feet (610 m). In steep country (>50 percent slopes), if road spacings are decreased, it generally means the road will require switchbacks to gain elevation. This was the case for the experimental portion of Abbot Basin road 590-B, as seen in figure 2 and appendix figures 18 and 19.

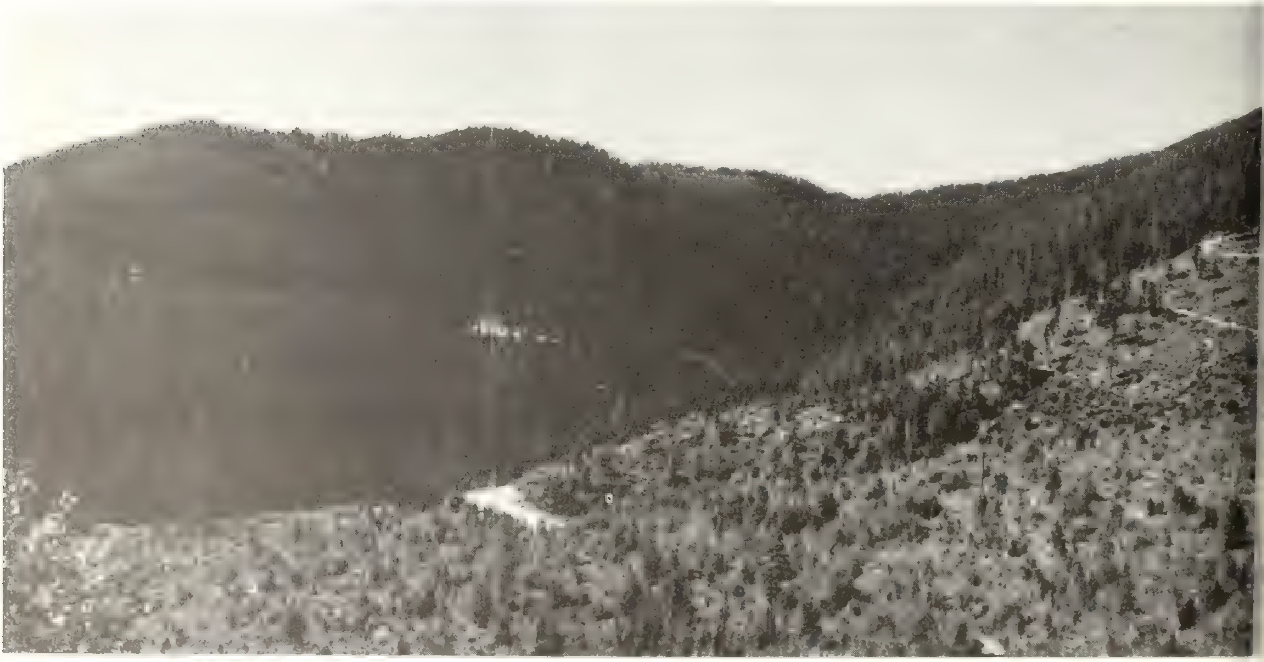

Figure 15.--Abbot Basin before construction of logging study road.

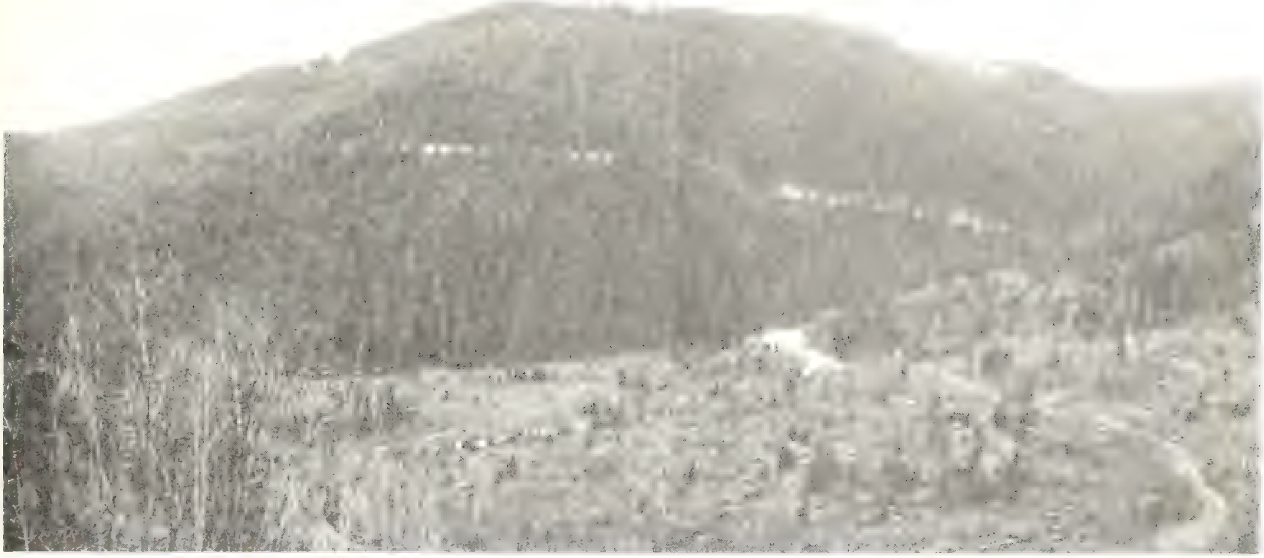

Figure 16.--Abbot Basin after construction of logging study road.

DISCUSSION AND CONCLUSIONS

In the future, an important consideration for construction of forest roads will be to reduce the environmental and social impact while still providing access needed for resource utilization.

For the experimental road on the Coram research site, a decision was made to reduce elements of design to the near minimum needed for operation of the logging equipment and evaluate the results. The road is located on an experimental forest and is a system road, but subject to atypical volumes of traffic because it is dedicated to research experimentation. Therefore, the road was evaluated for both the traffic associated with experimental logging and traffic assumed for a typical system road.

For the experimental sale, the single-lane road clearly was the best choice, environmentally. For a system road carrying normal traffic, including timber volumes of up to 4- to 5-million bd. ft. (15,840-19,800 m^3) annually, the reduced environmental impacts of a well-designed and well-constructed single-lane road may still be available at some acceptable level of economic sacrifice. For heavier volumes of traffic, especially logging traffic, then the trade-offs become more significant and require more difficult decisions about standards.

Estimated hauling cost differences for a wider single-lane road and a double-lane road for two assumed traffic volumes (10 VPH and 5 VPH) showed the 5 VPH traffic near the break even point for single-lane vs double-lane roads related to hauling cost for this sale.

Although final reports are not yet available from the results of esthetic and hydrologic impacts and revegetation experiments, some general observations are possibl Esthetic impacts of a single-lane road with reduced clearing widths definitely appear have been an improvement over standard practices.

Although the hydrology has been changed, as it always is when logging and road construction are imposed on the land, there is no evidence to date of adverse impacts from sediment or changes in runoff and streamflow.

Early results from the revegetation experiments show good success from the shrub planting and the impregnated mulch treatment. The plantings and seeding experiments will be effective in reducing visual and environmental impacts.

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1960. Logging road handbook: the effect of road design on hauling costs. U.S. Dep. Agric. Handb. 183, 65 p. Washington, D.C.

Gardner, R. B.
1971. Forest road standards as related to economics and the environment. USDA For. Serv. Res. Note INT-145, 44 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

APPENDIX A

Alinement Experimental Section Abbot Basin Road 590-B

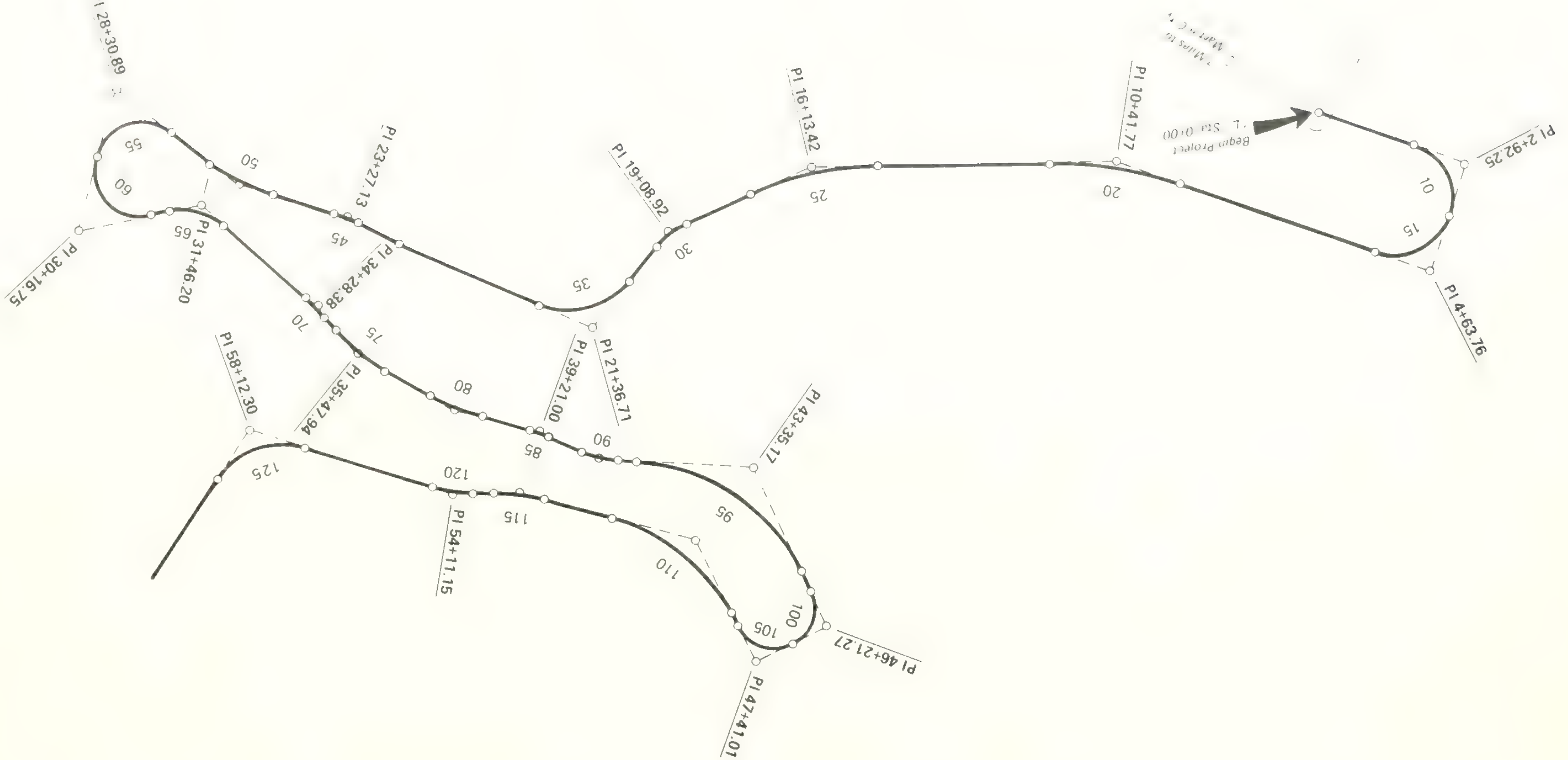
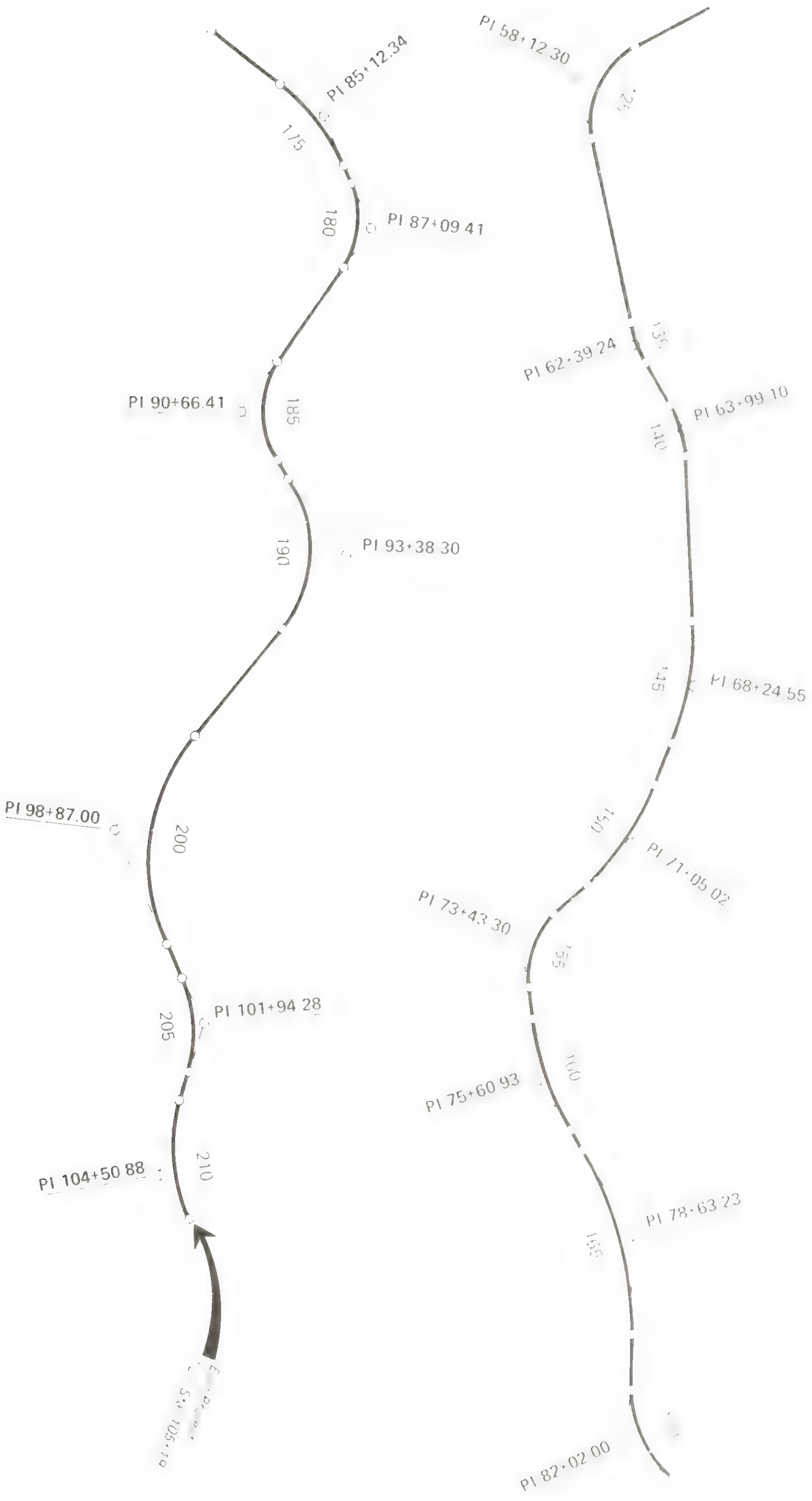
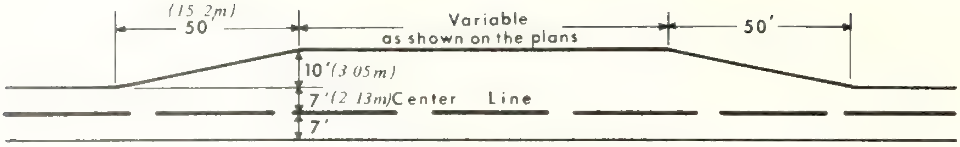


Figure 17.--Alinement--experimental section Abbot Basin road 590-B, stn. 0+00 to P1 58+12.30.

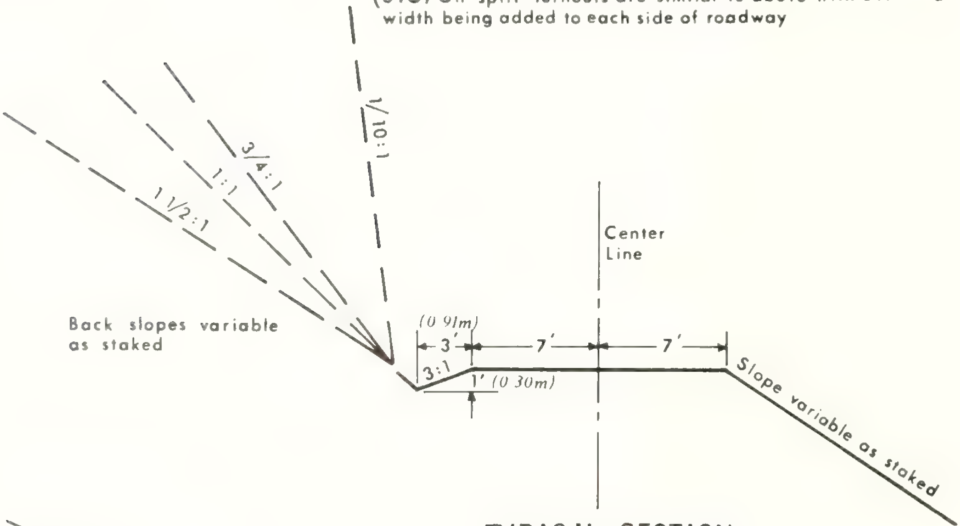

PI 58+12.30
PI 85+12.34
175
180
PI 87+09.41
130
PI 62+39.24
PI 63+99.10
140
PI 90+66.41
185
190
PI 93+38.30
145
PI 68+24.55
150
PI 71+05.02
PI 98+87.00
200
PI 73+43.30
155
PI 101+94.28
205
160
PI 75+60.93
PI 104+50.88
210
PI 78+63.23
165
105+70
PI 82+02.00



TYPICAL TURNOUT SECTION

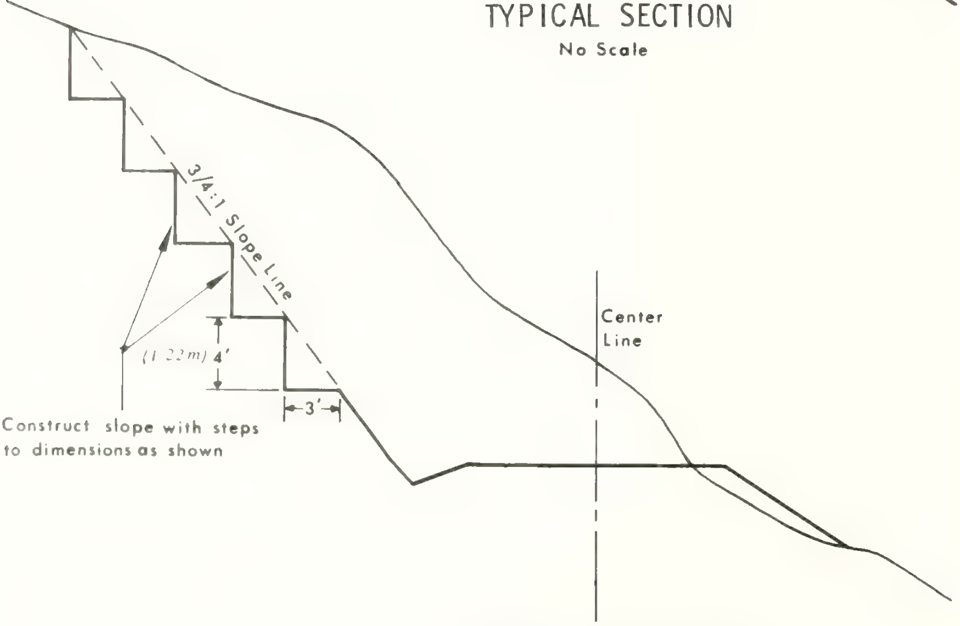
No Scale

(STO) On split turnouts are similar to above with 5ft extra width being added to each side of roadway



TYPICAL SECTION

No Scale



STEPPED BACKSLOPE

Sta 79 + 09 to Sta 83 + 53

No Scale

Figure 19.--Typical sections for turnouts, cut-and-fill slopes, and stepped backslope

APPENDIX B

Revegetation of Road Slopes . . . Shrubs and Grasses Planted

[illegible]

Species	Site 1		Site 2		Site 3		[illegible]		[illegible]		[illegible]		[illegible]	
	No. planted	%	No. planted	%	No. planted	%	No. planted	%	[illegible]	[illegible]	No. planted	%	No. planted	[illegible]
Woods rose [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	91	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Redosier dogwood [illegible]	[illegible]	100	14	91	-		[illegible]	[illegible]						
hokecherry [illegible]	516	87	62	[illegible]	[illegible]	7	[illegible]	86	59	95	—			85
Serviceberry [illegible]	[illegible]	[illegible]	[illegible]	76	[illegible]	8	03	95	66	82	151	[illegible]	928	[illegible]
Blackcap [illegible]	[illegible]	[illegible]	23	87										85
Spirea [illegible]	188	[illegible]	66	66	[illegible]	41	[illegible]	[illegible]						
lue elderberry [illegible]	[illegible]	[illegible]	-	-	-									
lack elderberry [illegible]	[illegible]	[illegible]	23	[illegible]										50
edstem ceanothus [illegible]	[illegible]	[illegible]	56	41	106	[illegible]	[illegible]	[illegible]	63	27	[illegible]		[illegible]	51
inebark [illegible]	68	75	25		-									
Beard tongue [illegible]	170	65	48	46	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]			
imbleberry [illegible]	[illegible]	[illegible]	24	-										
umac [illegible]	[illegible]	44	[illegible]	47										
untain mahogany [illegible]	—	-	29	[illegible]										
ergreen ceanothus [illegible]	322	21	[illegible]	[illegible]	[illegible]	16	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
Oceanspray (Holodiscus discolor)	[illegible]	1	[illegible]	[illegible]										
upine [illegible]	236	2	105	[illegible]			[illegible]	[illegible]						

Table 9.--*Grass and legume mixture used to seed slopes of experimental road.*

Species	Rate/acre	Kg/hectare
	Pounds	*(Kg)*
Alta tall fescue	2.5	(2.81)
Manchar smooth brome	4.0	(4.49)
Orchardgrass	2.5	(2.79)
White Dutch clover	2.0	(2.25)
Birdsfoot trefoil	2.0	(2.25)

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Gardner, Rulon B.
1978. Cost, performance, and esthetic impacts of an experimental forest road in Montana. USDA For. Serv. Res. Pap. INT-203, 28 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

An experimental logging road designed to minimize environmental and esthetic impact was constructed in northwest Montana. The road was single-lane (14-foot finished surface, 3-foot ditch), constructed along the contour. Esthetically, the single-lane experimental road was judged far superior to existing roads on the forest.

KEYWORDS: forest roads, logging roads, road design, environmental impact

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USDA Forest Service Research Paper INT-[illegible]
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE U.S. DEPARTMENT OF AGRICULTURE

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USDA Forest Service
Research Paper INT-204
April 1978

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RESEARCH SUMMARY

Erosion caused by road construction on the steep, fragile, decomposed granitic soils of the Idaho Batholith resulted in a 1965 moratorium on road construction in the South Fork of the Salmon River and its tributaries.

In 1970, the China Glenn Road was built to salvage trees attacked by the Douglas-fir beetle and protect the residual stand. It was constructed well back of the river-break zone on slopes averaging 40-50 percent. A key objective was to build a road with as little environmental impact as possible. A single-lane (12-foot (3.66 m)) road following the contour without a ditch, and with special design features, has proved adequate for logging, with little adverse impact.

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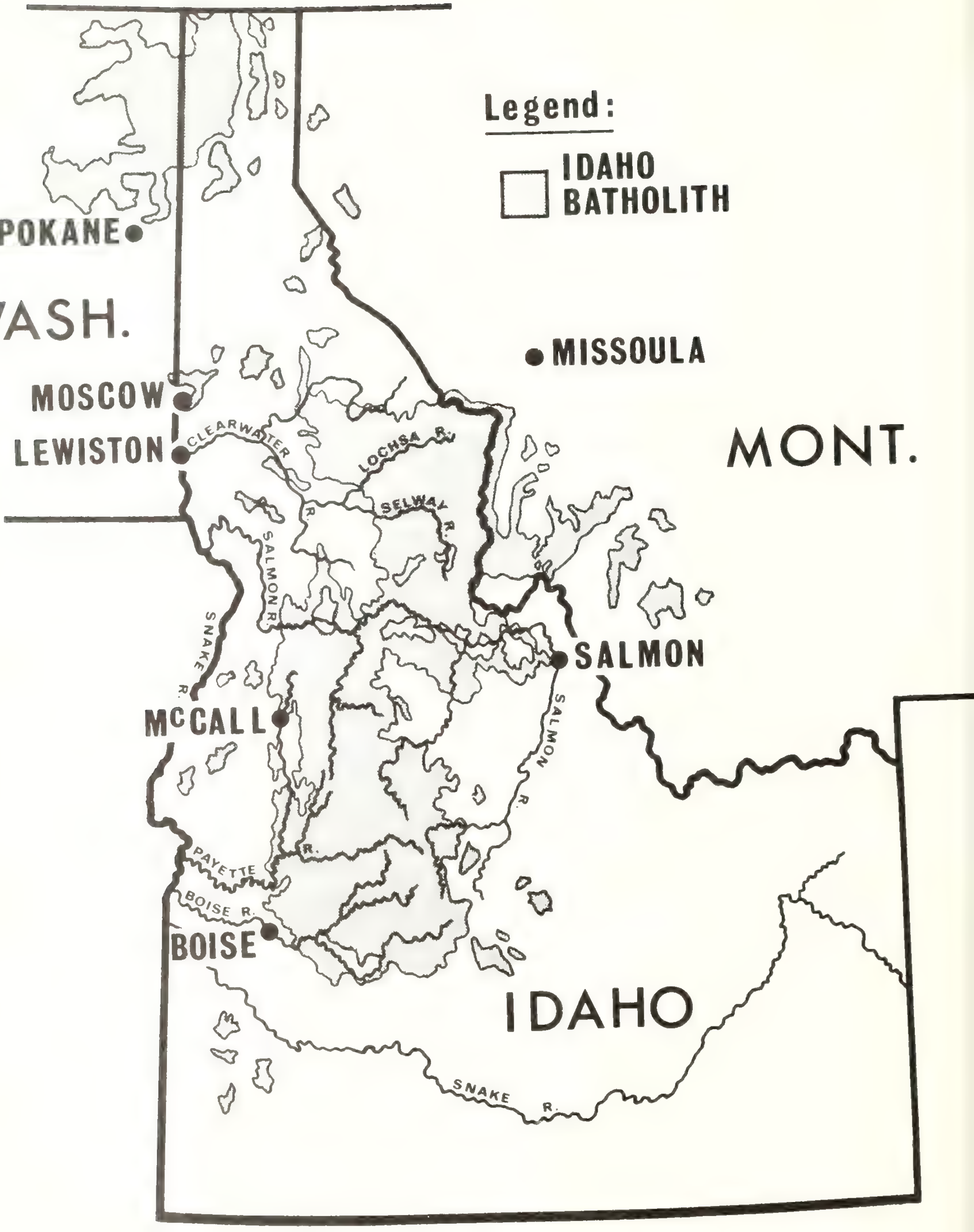


Figure 1.--The Idaho Batholith.

INTRODUCTION

The fragile, steep, decomposed granitic slopes of the Idaho Batholith (fig. 1) present many special problems for the construction and maintenance of stable forest roads. Some early recognition of this (1958) resulted in a joint administrative-research study by the Intermountain Region and Intermountain Forest and Range Experiment Station, both of the Forest Service, U.S. Department of Agriculture. The study was in Zena Creek on the Payette National Forest and was designed to help determine if the steep slopes could be logged economically with tolerable impacts on the environment.

Although there was an awareness that roads could contribute significant volumes of sediment, especially during critical periods of runoff, the results proved to be more serious than anticipated. Studies following road construction (1958-60) in Zena Creek by Haupt and others (1963), Gonsior and Gardner (1971), and Megahan and Kidd (1972) document the impacts of the road construction. Excessive erosion occurred the first year or two on both insloped and outsloped roads. Later in December of 1964 and April 1965, rain-on-snow storms produced extensive damage, this time from road slope failures.

As a result of these experiences, a moratorium on road construction in the South Fork of the Salmon River drainage was declared in 1965 until research and experimentation could better identify the problems and develop methods for reducing impacts to acceptable levels.

In 1969, an entomological detection flight in the South Fork drainage found a large and expanding population of Douglas-fir beetle (*Dendroctonus pseudotsugae* (Hopk.)) that had already damaged many trees and threatened many others. A decision was made to build the China Glenn Road into the infected area to salvage the bug-killed material and protect the residual stand. This road could be built well back from the river-break zone and in much less sensitive terrain than the Zena Creek roads. Also, the design would incorporate criteria that were known from experience to reduce impacts, including what was learned in Zena Creek.

The engineers and resource managers both desired to build a road that would serve the needs of the loggers, but not inflict excessive damage on the land and water resources. This report (1) reviews the initial design and performance of the China Glenn Road as reported by Hartsog and Gonsior in 1973, (2) describes the redesign of the second section of the road, (3) compares the guidelines used on the first and second sections of the road, and (4) gives a list of suggested road design principles to be used in the Idaho Batholith.

REVIEW OF THE INITIAL DESIGN AND PERFORMANCE OF THE CHINA GLENN ROAD

Although it is standard practice to utilize a multidisciplinary approach for the planning of transportation systems, the China Glenn road received extra attention because it was the first road constructed in the Batholith since the moratorium was imposed. The China Glenn Road thus became a test of some principles that needed verification and a learning experience for those interested in road construction methods i the Batholith.

Because of the necessity for quick action required to protect the stand and the short lead time given the research group, there was not enough time to set up detailed research experiments to help evaluate the results. However, one study of settlement of a through fill was attempted without conclusive results. The engineering research staff in Bozeman, Montana, was invited to participate in reviewing the proposed design and make suggestions based on their experience in Zena Creek. They were also involved in observing construction and helping to evaluate the results.

Location and Design

The major objective of location and design was to reduce impacts as much as possible and still provide reasonable service to the traffic. Access to the general area was provided by an existing system road.

Because of the desire to reduce impacts, a 12-foot-wide (3.66 m) (without ditch), single-lane road with turnouts, a 90-foot (27.36 m) minimum radius of curvature, and maximum grade of 10 percent constituted the basic design criteria (grade averages 2.7 percent). Fill slopes were designed on a minimum slope of 1-1/2:1, and cut slopes generally 1:1. When natural ground slope was 55 percent or greater, full bench construction was used (fig. 2). This was done to help avoid long sliver fills (fig. 3). Soil testing showed that it was possible to achieve the desired compaction with the construction equipment and normal traffic use. (The decomposed granitic material in the entire South Fork has very similar characteristics and, therefore, has similar reactions to the forces of water and traffic use.)

Two general land types were encountered--weakly dissected mountain slope land, deep sandy soil; and moderately dissected mountain slope land, moderately deep sandy soil. In a system used to classify soil and land types in the Idaho Batholith, they are mapped and classified as 120a and 120b, respectively.[1]

Water control, of course, is vital to stability. Care was taken to try to prevent any significant volume of water from developing on the road by the use of outsloping, grade breaks, and culverts for natural drainage channels--culverts were installed in virtually every draw.

---

[1] Thompson, Richard A., Paul E. Skabelund, and Norbert C. Kulesza. 1973. Soil-hydrologic reconnaissance, McCall Ranger District, Payette National Forest.

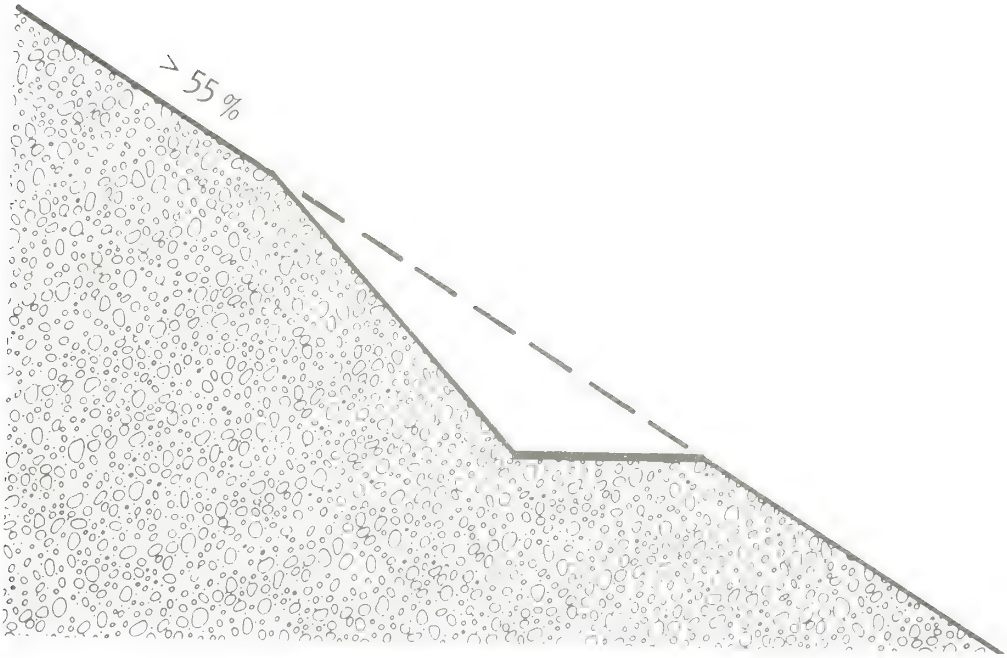


Figure 2.--Fill bench.

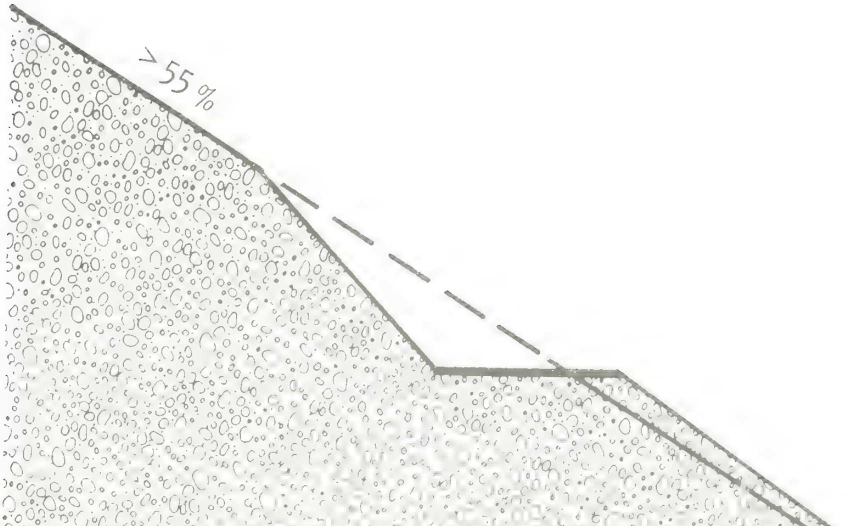


Figure 3.--Sliver fill.

The above describes the basic parameters and the general philosophy of design. Th following sections cover observations made during and after the first year's construction, decisions, about design changes following those observations, the results of thes design changes, and recommendations, and guidelines for future design of roads in the Batholith.

CONSTRUCTION/PERFORMANCE — FIRST 2.25 MILES (3.62 KM)

Construction

Construction began the last week of July 1970 and continued into September. About 2.25 miles (3.62 km) of the total of 3.48 miles (5.60 km) were completed the first year.

An important point to mention about the road in general, before some detailed observations, is that land managers' and engineers' backgrounds give them a somewhat different ability to visualize, from looking at a set of road plans, what the final product might look like on the ground. There were some differences between the results envisioned by the land managers and actual results on the first section constructed. How these concerns were accommodated in the design of the second section will be the subject of further discussion later. (Perhaps the developing use of computer graphics will help alleviate this problem in the future.)

Because some design changes were made after the first year of construction, it is necessary to separate some of the observations of results. Because the clearing operation was essentially the same for the entire job, it is discussed first.

Clearing

Clearing a right-of-way on slopes averaging 40-50 percent is a difficult operatio especially while trying to protect the environment and the integrity of the road. To gain reasonable access to operate with the equipment available, a pioneer road was bui as is the custom. The construction of a pioneer road constitutes probably the most tr- blesome problem of the whole operation. The difficulty lies in the problem of prevent slash and unmerchantable logs (merchantable logs are decked outside of the right-of-wa that will be burned from ending up in the road fill or having excessive quantities of loose soil mixed in with the slash piled at the toe of the fill. The operator in this case was reasonably careful, and the results were about as good as can be expected using present equipment and methods.

Customarily, slash is burned. Here, the slash at the toe of the fills was not burned the first year after construction, and it acted as an efficient trap for sediment from the fill slopes. This brings into question what the most desirable disposition of slash might be when there is a potential beneficial use for it--to be discusse more later. This is the extent of the observations of clearing for which some recommendations will be made in the Conclusions.

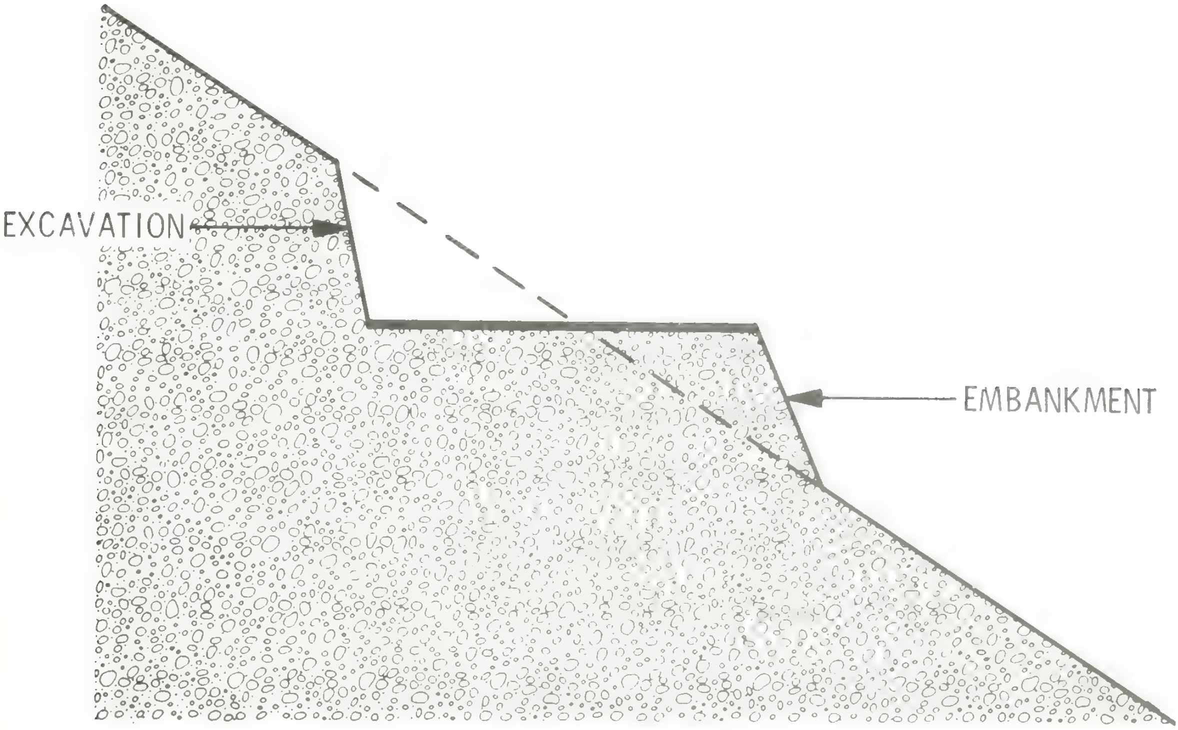


Figure 4.--Sidecast section.

Grading and Drainage

Grading refers to the earthmoving and placement operations that were primarily accomplished with "U" dozers. (A U-shaped dozer blade facilitates drifting material between balance points.) Because this was essentially a contour road, most of the road was constructed by sidecasting excavation to provide embankment, as seen in figure 4. Balance points were generally fairly closely spaced, and material from ridges was readily available for through fills crossing draws.

A D-8 cat with a 14-foot (4.27-m) blade was used to move most of the excavation, and herein lies a problem common to constructing any 12-foot-wide (3.66-m) subgrades with large equipment. It is virtually impossible to obtain good compaction for much of the embankment because the 11.5-foot (3.51-m) (outside span) tracks remain essentially in the same position on the road. Also, it isn't possible to compact the area near the toe or often to even work the material out to the fill stake. This results in some of the fills being on slopes slightly greater than the design slope of 1-1/2:1.

The drainage design of outsloping, grade breaks, and culverts in almost every draw was carried out according to plan. However, the culverts proved to be somewhat over-designed with many not carrying any water even during the 4-day, Labor Day weekend storm. The storm produced 2-3 inches (5.1-7.6 cm) of rain.

Performance

Control of subsurface and surface water flows is the key to stability from erosion and mass failure. As discussed earlier, outsloping, grade breaks, dips, and adequate drainage for natural channels were designed for this purpose. Contouring into draws, to the extent possible with 90-foot (27.36-m) minimum radius, helped keep through fill heights down. Employing these techniques produced a road that has functioned very well considering the difficult soils of the Batholith. In fact, the following photos and discussions show basic stability remains 6 years after construction without any maintenance for the past 5 years.

Outsloping/Insloping/Grade Breaks/Berms

In figures 5 and 6, it is apparent that control of surface water has been maintain by the judicious use of outsloping, design dips, and breaks in grade. In figures 7 and 8, insloping was used with berms to direct surface water to the cross-drain culverts. Although the road is primarily an outsloped road, there were occasions when water could not be carried to a full bench section or transition point from fill to cut to be dispersed on natural ground. When this occurred, as shown in figures 7 and 8, insloping and berms were used. Because of the difficulty of maintaining berms, and the extra road width required for their use, they were employed only when other means could not be used.

Fill-and-Cut Slopes

Since most of the sidecast fill slopes are short (less than 20 feet (6.10 m) long) and they are built on natural ground slopes of 50 percent or less, there have not been any failures, even through some slopes are steeper than 1-1/2:1. Part of the success of fill slope stability to date can be attributed to the fact that good drainage has prevented any of the fills from becoming saturated.

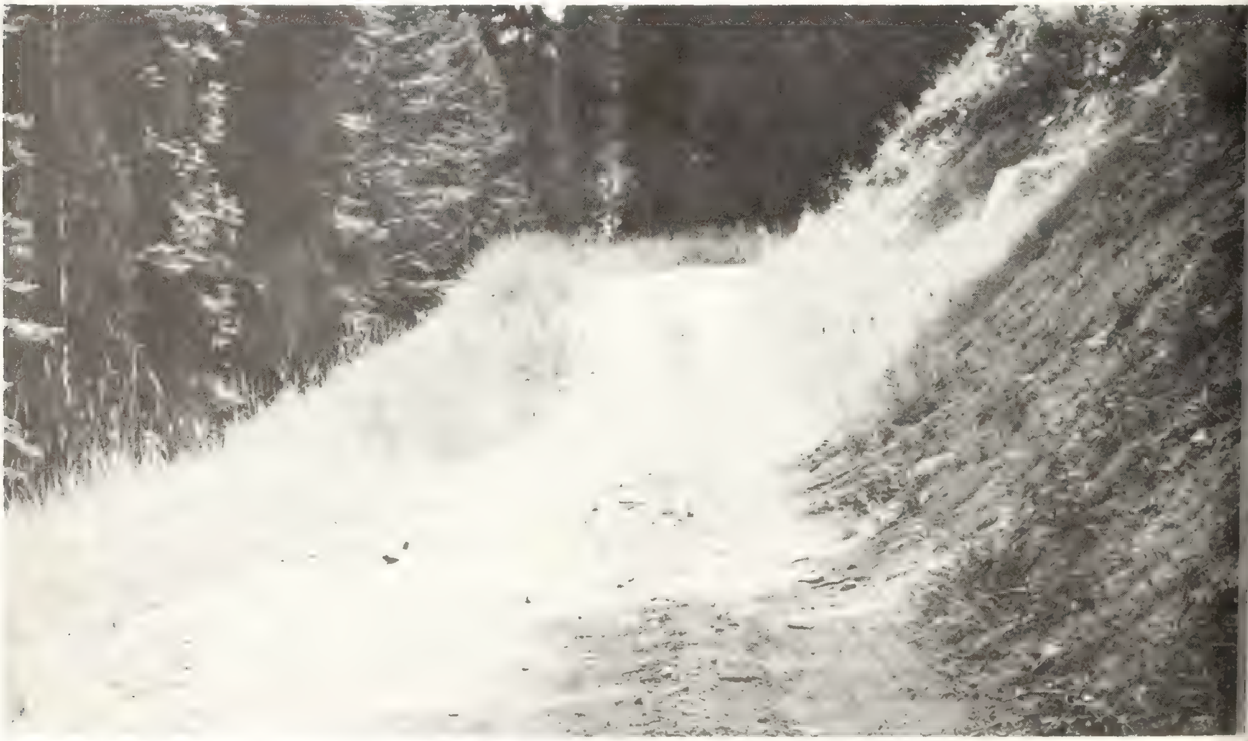


Figure 5.--Outsloped section with dip (built after construction).

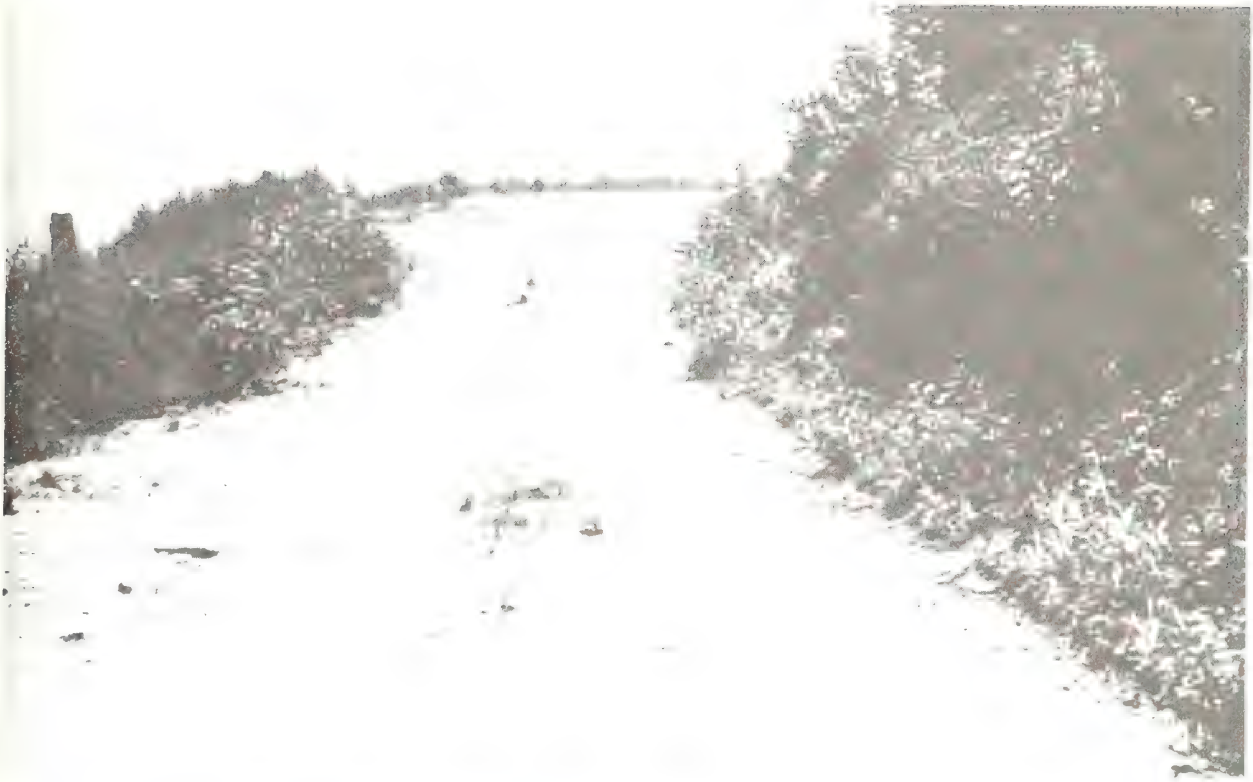


Figure 6.--Break in grade, with dip followed by turnout on outslope section.

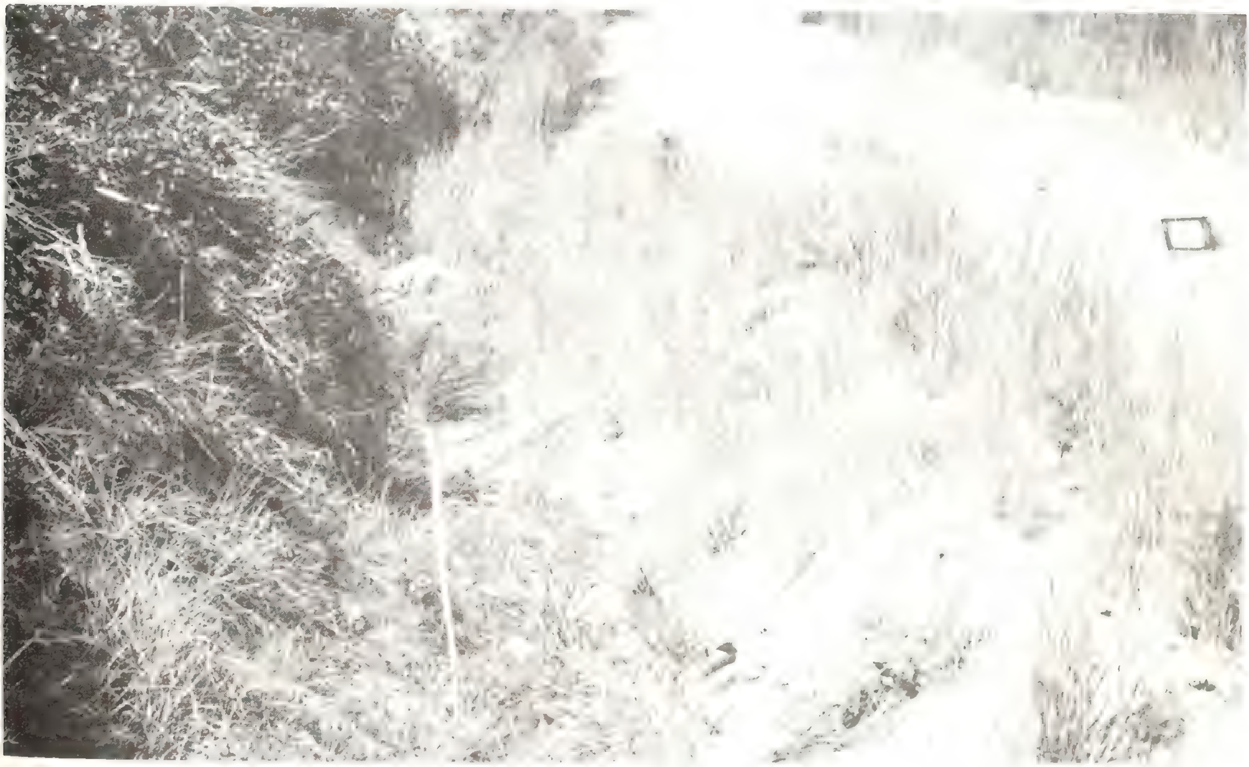


Figure 7.--Inslope to culvert for cross drainage at break in grade.

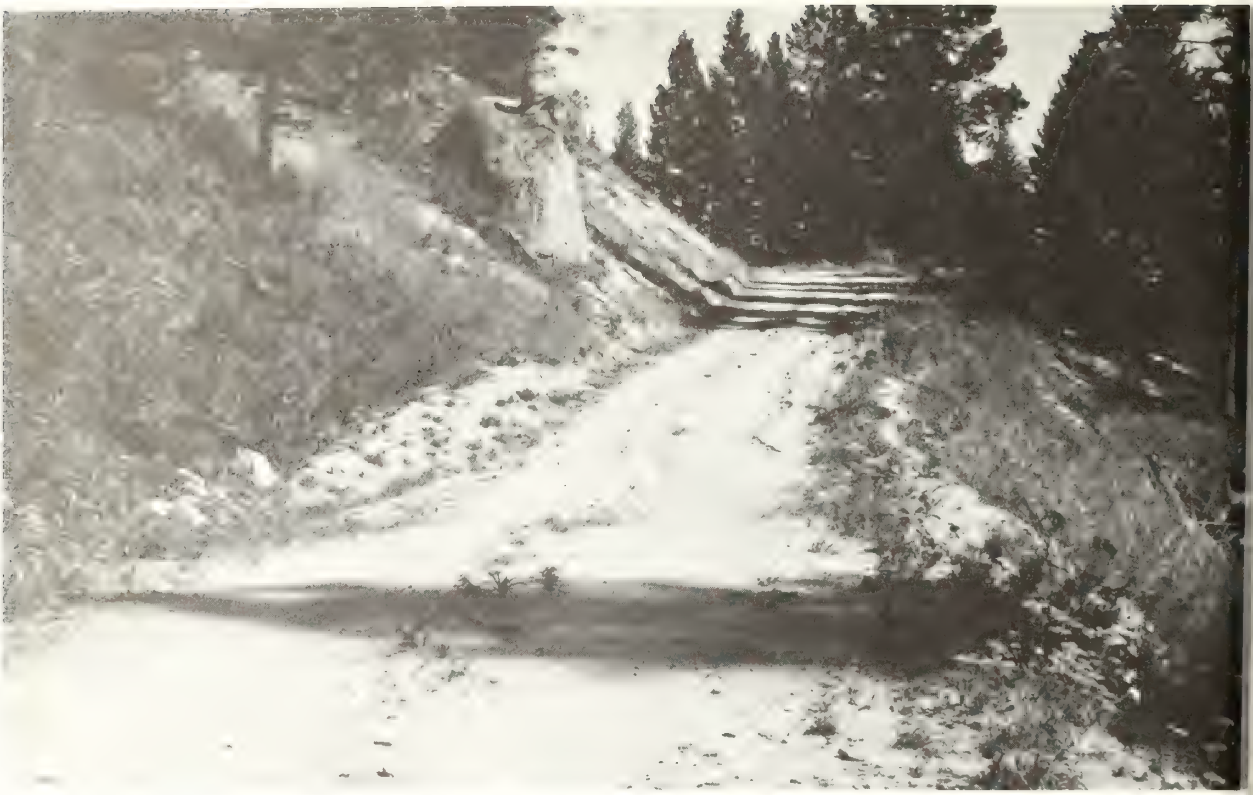


Figure 8.--Insloping to dip with berms controlling flow.

In figure 9, a typical section of stable sidecast fill is shown.

Since natural ground slope seldom exceeded 50 percent, it was generally possible to use 1:1 backslopes for cuts without opening up excessively long raw slopes. (When slopes exceeded 55 percent, full bench construction was used to eliminate sliver fill) Figure 10 shows a typical section of cut slope that is relatively short and obviously stable.

Culverts

No culverts have failed to date and none are expected to fail. However, culvert in some small draws have not carried any water to date.

Revegetation

The revegetation success with cut slopes has been generally good, and fill slope excellent (fig. 9 and 11). Seeding specifications are given in the following tabulat n:

Revegetation--Grass Specification

Seed	*Percent*
Intermediate wheat	50
Smooth brome	15
Timothy	15
Orchardgrass	15
White clover	5

(In addition, 2-year ponderosa pine stock was planted on through fills to enhance stability on a 5- by 5-foot (1.52- by 1.52-m) spacing using an auger with good succes)

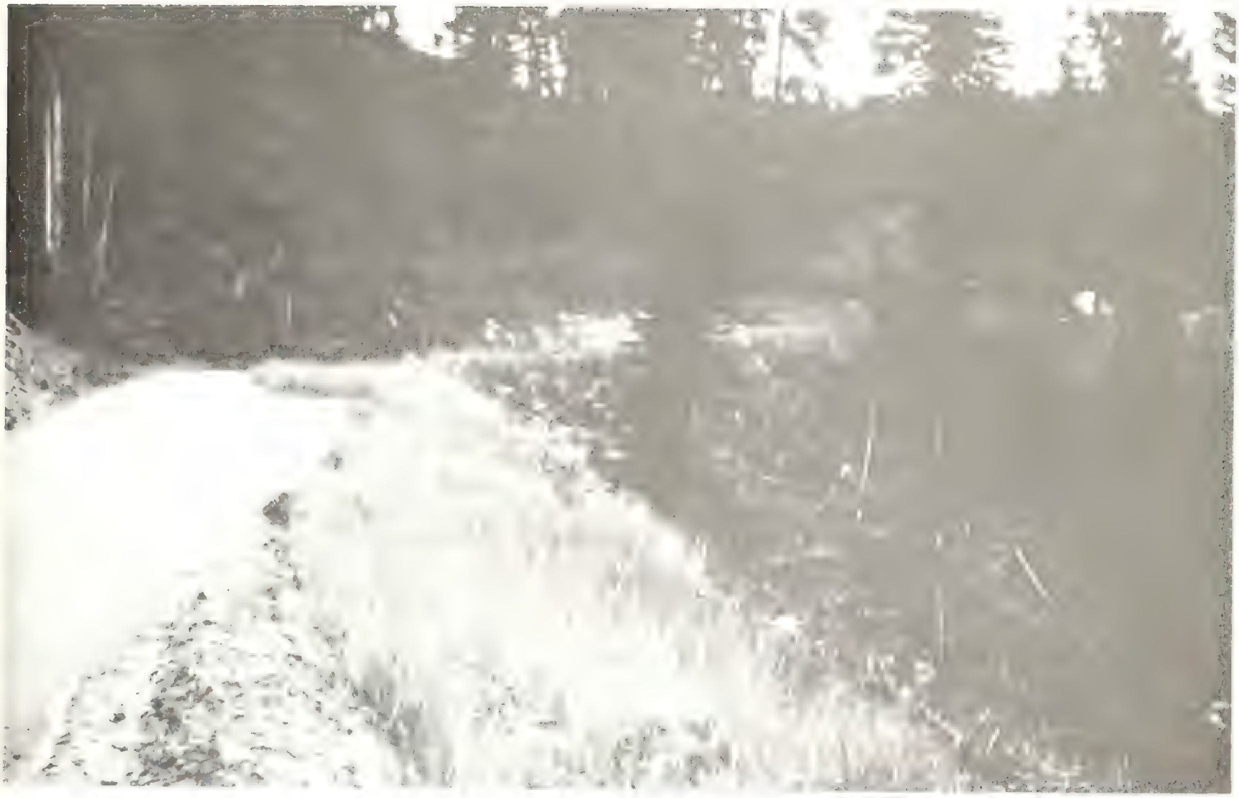


Figure 9.--Typical section of stable, sidecast fill.

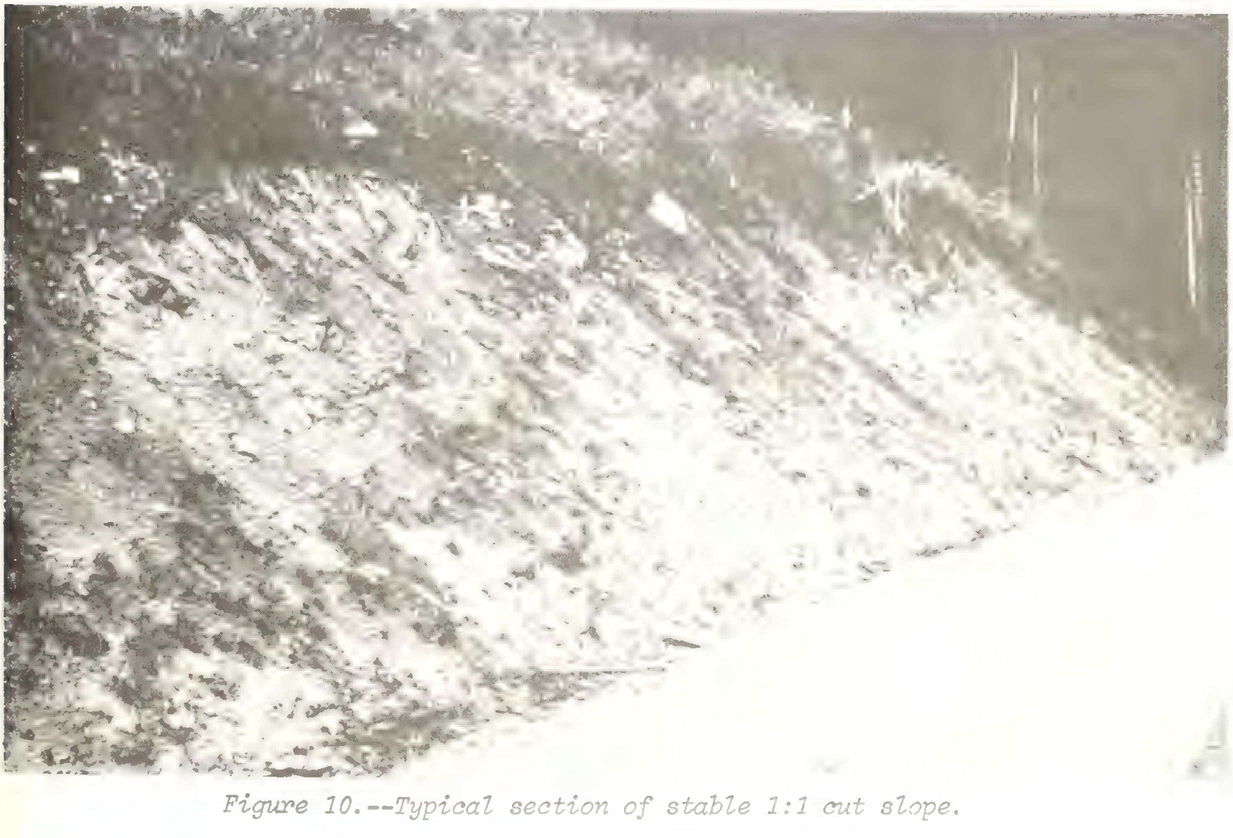


Figure 10.--Typical section of stable 1:1 cut slope.

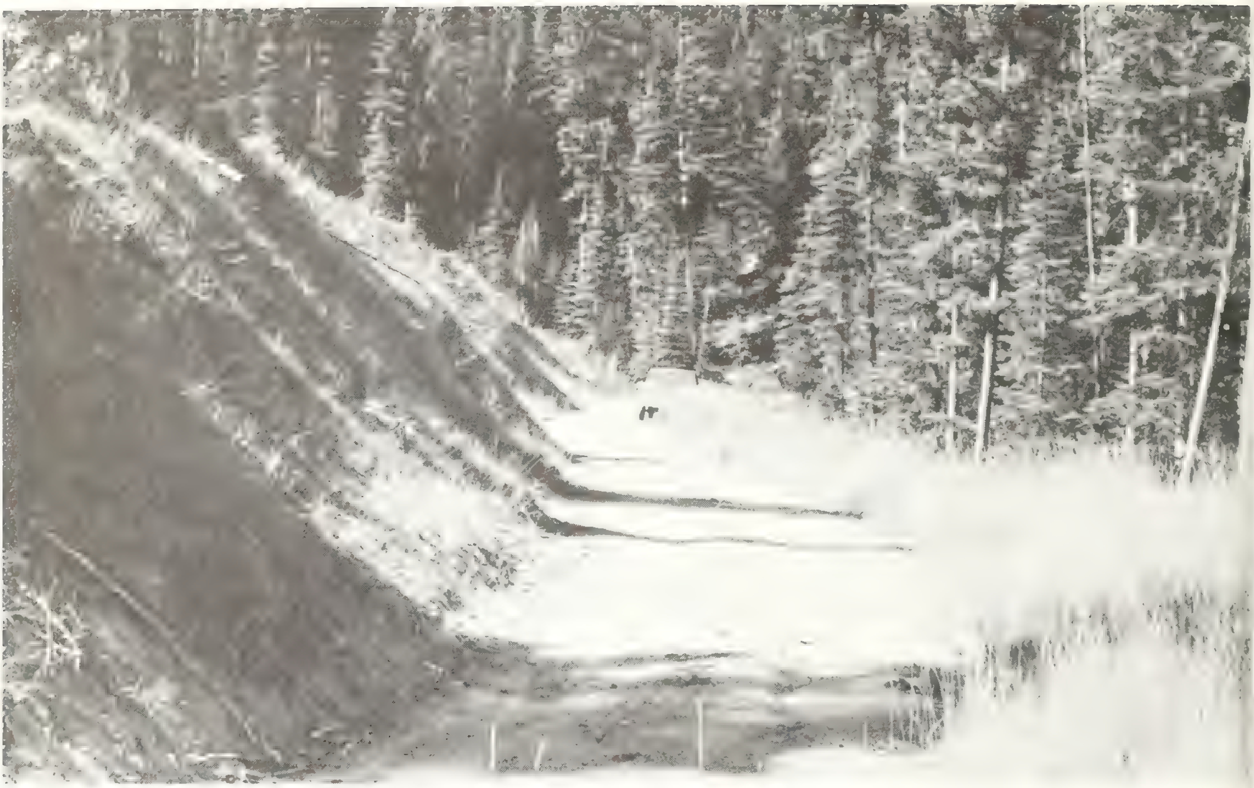


Figure 11.--Revegetation of cut-and-fill slopes.

Summary

The usual problems with clearing in steep terrain and construction of narrow, single-lane roads with equipment large enough to efficiently perform the job were encountered. However, since the construction was completed, the performance of the road to date has been good for the difficult conditions in the Batholith.

The general design philosophy was effective in attaining control of water and producing a stable road. However, the designers and research cooperators both felt that some lessons had been learned that could be applied and should be tried for the balance of the road to be constructed the following year.

The next section of the report will discuss the redesign and performance of the second section of the China Glenn Road.

REDESIGN AND PERFORMANCE OF THE SECOND SECTION OF ROAD

The key point that prompted a redesign of the second section was the difference in the final appearance of the road from what was visualized by the resource managers. The primary concern was the area opened up by construction of the road. Two other important points were:

--a modified dip design, that would have less effect on trucks negotiating it than the standard design, would provide adequate control of surface flow, and

--fewer culverts were needed for minor draws than originally designed.

Because the China Glenn Road was a multiple use road, the minimum standard practice for safety and other guidelines were used for the original design. These guidelines are not hard and fast rules, but were developed over the years and are established practice. The original design employed such common practices as minimum radius of curvature of 90 feet (27.36 m), minimum backslopes of 1:1 in common material, and a generally sustained grade. These standards, as viewed by the engineers, would produce a road with no more impact than necessary to maintain reasonably safe standards for a system road. The resource managers visualized a road that would meet the absolute minimum needs for removing timber from the area. It was felt that a compromise between these views was a reasonable goal to try to attain for the second section.

Following is a discussion of the guidelines and criteria used for the redesign.

Guidelines for Redesign

It is seldom possible to design a road that achieves all of the major objectives of all concerned; therefore, it is usually necessary to determine objectives that have priority and to modify other desirable objectives. In the case of the China Glenn redesign, the primary objective for the design of the second section was protection of soil and water resources.

To better protect these resources, the designers attempted to improve the redesign in the following ways: (1) expose a minimum of soil to the effects of weathering and erosion (especially from runoff and raindrop impact erosion), (2) control runoff water during, as well as after construction, and (3) disrupt natural drainage patterns as little as possible.

Road travel surface width is determined by minimum use needs; therefore, the exposed soil surface sections of the road prism that can be reduced are sometimes confined to the cut-and-fill slopes. Often little can be done to reduce the quantity of soil exposed on granitic fill slopes as oversteepening could lead to more serious problems, such as failure of the fill. However, construction of cut slopes as steep as feasible and fitting the road horizontal and vertical alinement to the contour of the land were methods to be emphasized to reduce soil exposure and thus keep excavation volumes to a minimum.

Guidelines for Cut Slopes

It was decided to try near-vertical cut slopes as long as they did not exceed 6 feet (1.83 m) in height, otherwise a 1:1 slope was used. It was felt that if a 6-foo vertical slope sloughed, it would not result in much infringement on the travel surface Since the timber adjacent to the road was to be logged the same season that the road was constructed, all logging truck traffic would take place before any spring sloughing could occur. The type of traffic anticipated after the first spring would be normal management and recreational traffic, which would not require the full orignal width (12 feet (3.66 m)).

Guidelines for Grade and Alinement

Horizontal and vertical alinements were adjusted to obtain as many balanced sidecast sections as possible. The balanced sidecast road requires a minimum of earth movement and is especially efficient on steep sidehills.

The China Glenn Road is generally located on terrain that made it possible to roll the vertical alinement in conjunction with adjusting the horizontal alinement to obtain a balance between cut-and-fill. (Often in mountainous terrain, steep grades do not allow rolling the vertical alinement, and attempts to keep the earthwork balanced have to be made by adjusting the horizontal alinement only.) Two advantages of being able t roll the grade are: first, the earthwork can be held at a near balance condition while maintaining a better horizontal alinement; and second, the rolling grade helps provide drainage control and allows the road to better fit the natural drainage patterns of the area.

Guidelines for Clearing

Right-of-way clearing was restricted to help control sliver fills.

The first section of the China Glenn Road was cleared in accordance with "good" sight distance criteria for logging road construction. Horizontal clearing limits were set at 10 feet (3.05 m) beyond the top of cut banks and 5 feet (1.52 m) beyond the toe of fills, or 16 feet (4.88 m) each side of centerline, whichever was greater.

It was decided to allow fills to build up to a maximum height of 2 feet (0.61 m) on the trunks of the trees along the toe of the fills (as long as this point was at le 16 feet (4.88 m) from the road centerline).

Another design change was to pile slash of 4 inches (10.1 cm) or less diameter al and below the lower edge of the fill. The slash would act as a catchment to help cont any eroded fill material. Placing living or dead material along the toe that may end up supporting part of an embankment is not considered good engineering practice; howev after considering the nature of the intended use and the characteristics of the area, advantages of using a slash catchment seemed to outweigh the disadvantages.

Guidelines for Turnouts

Turnouts were installed at locations that minimized earthwork. Desirable locatio for turnouts are gentle slopes. When earthwork is minimized, esthetic impacts and ero sion are reduced. Turnout locations, of course, should always be located with conside ation for sight distance and safety. This guideline was followed on the original road and the redesign, so there were no appreciable differences in this case. (There were 11 turnouts in the 6,500 feet (1,976 m) of the redesign.)

Guidelines for Drainage

The need to control runoff during construction was demonstrated by the Labor Day storm of 1970 (described in the first report in this paper), which damaged the first section of the road before it was completed.

The general objective was to control runoff water during, as well as after, construction by installing corrugated metal pipe, roadway dips, and an alternating outslope-inslope road surface as needed to take advantage of stable surfaces for discharging water.

Drainage for live water and draws was provided by appropriately sized, corrugated metal pipe, and cross drainage was provided by dips constructed in the roadway. Drainage control was basically the same for both the original and the redesign. However, the redesign was adjusted as a result of experience gained after the first section was constructed. For example, less drainage for draws was called for in the redesigned section because it was found that many of the culverts on the first section didn't carry water either during the Labor Day storm or during spring runoff. The dry culverts were in small draws that are common to the area. Because infiltration (natural permeability) is generally good in the Batholith, overland flow is uncommon outside of ephemeral streams.

Dips were not included in the original portion of the road's design grade because they can be troublesome for the logging trucks to negotiate. Truck drivers dislike dips constructed as specified by the Forest Service standard design because the dips deflect the trucks off the road during slick road conditions and also impose a twisting stress on trailer frames. Dips used in the redesign were modified to reduce the sliding hazard and stresses on trucks. The first modification consisted of keeping the dip the same depth across its full width, relying completely on the normal 3-5 percent outslope or inslope to keep the dips drained. The second modification was to make the dips perpendicular to the centerline of the road rather than skewed. This allows all the wheels on the same axle to negotiate the dips evenly, thereby eliminating the twisting action on the trailer frames. The dips were 1 foot (0.30 m) deep and 100 feet (30.40 m) long. The profile of a typical dip is shown in figure 12.

The 1-foot (0.30-m) depth is measured between the elevation of the dip bottom and the elevation of the downgrade end of the dip 35 feet (10.69 m) away. The vertical height between the dip's bottom and the projected sustained grade varies according to the magnitude of the grade. The height for the above example in figure 12 is 2.98 feet (0.91 m). It can easily be seen that as the grade increases, so does the impact of these dips to the road user. The dips, as described, caused no apparent distress to logging truck traffic.

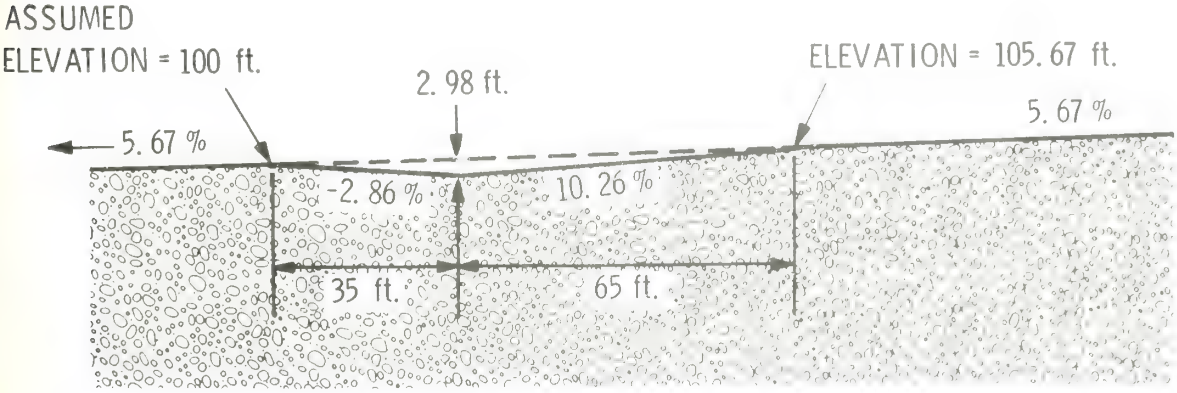


Figure 12.--Typical dip profile.

COMPARISON OF THE GUIDELINES USED ON FIRST AND SECOND SECTIONS OF THE CHINA GLENN ROAD

There are no quantitative measurements of impacts on either section of road, and opinions differ between observers. However, there are some obvious differences in some of the parameters that undoubtedly had some effect on impacts.

Construction

The second year's construction began July 1, 1971, and was completed in mid-Septem

Clearing

The problems associated with clearing were discussed in the first section of the report and were generally the same for the second section.

Total clearing area for the redesign was 6.61 acres (2.68 ha), which was 26 percen less than the original design. Of this 6.61 acres (2.68 ha), 83 percent occurred insi the minimum clearing limits of 16 feet (4.88 m) each side of centerline. Eleven percen was outside minimum clearing limits on the cut side of the road, and only 6 percent occurred outside minimum clearing limits on the fill side. Through fills over stream crossings are included in this 6 percent, which indicates that most sliver fills of th type found on the original design were eliminated.

Grading and Drainage

The same equipment was used for both sections of the road, and the same general difficulties encountered on section 1 also apply to section 2. There was one importan difference in construction for section 2--the dips were staked and built as the grade was constructed. This was done to control drainage during construction. Another advan tage to this practice is that the dips are compacted with the rest of the road and therefore are more stable.

Outsloping/Insloping/Rolling Grade/Dips/Berms

The difference between the two sections of road in these categories is primarily the use of grade rolling and the dip design in the second section discussed earlier. In figure 13, a transition section (inslope to outslope) is shown. This is an example of good design working well, controlling flow. Figure 14 shows a dip in a section of sustained outsloped grade. The appearance of the unmaintained road surface shows that drainage has been adequately controlled.

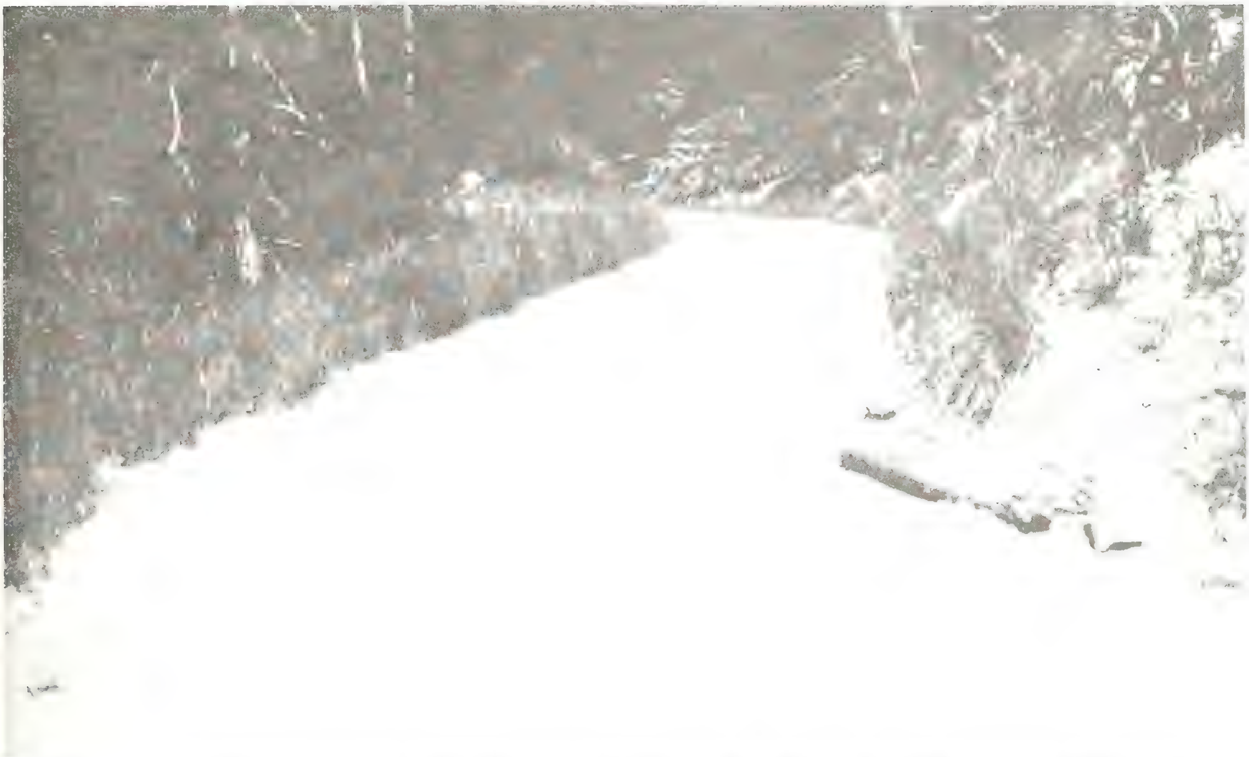


Figure 13.--Transition from outslope to inslope just past the curve is an example of good design functioning well.

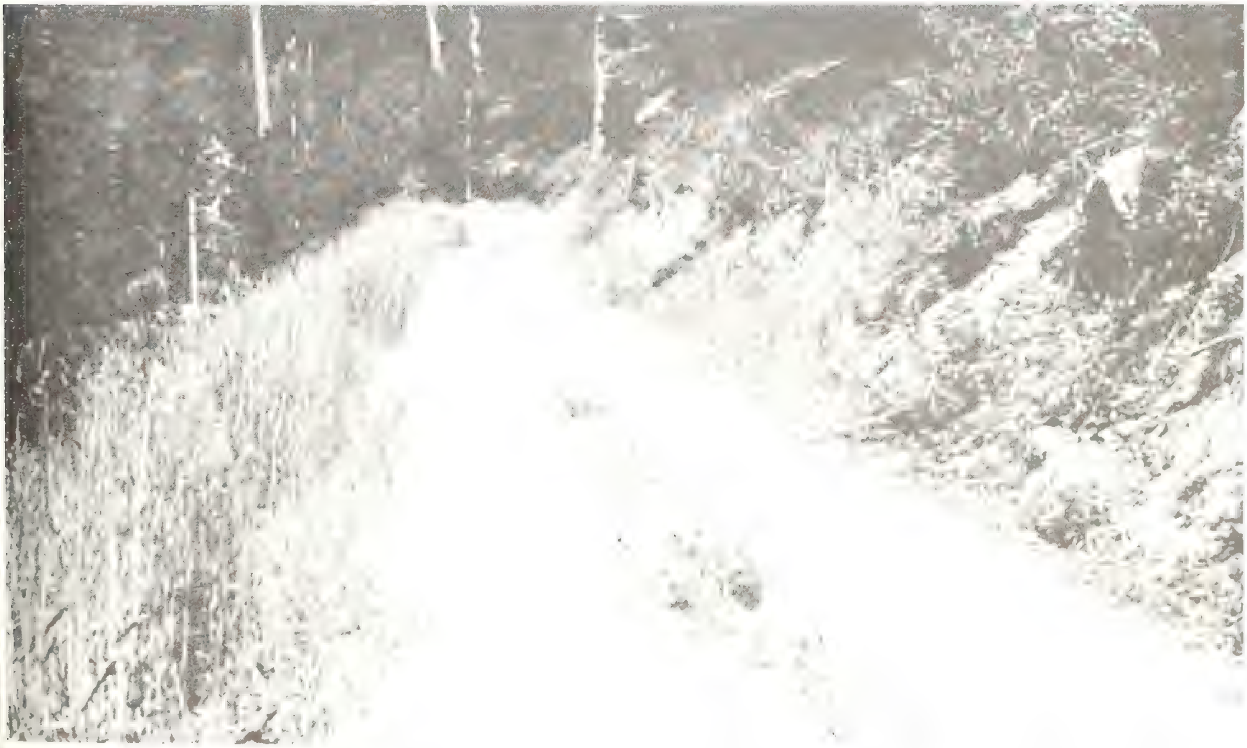


Figure 14.--Dip near the end of a section of outsloped road on a sustained grade.

Fill-and-Cut Slopes

Both fill-and-cut slope heights are less in section 2 because of the vertical cuts used for slopes 6 feet (1.83 m) and under and more rolling of grades and contouring. The advantages of contouring and grade rolling to generally reduce cut-and-fill heights are obvious. However, opinion is divided on the use of vertical cut slopes. The genera problem of designing vertical cut slopes is much the same as it has always been--short vertical slopes function quite well in the better drained soils that also exhibit some cohesiveness, and not so well in the poorer drained, heavier soils. The problem is in identifying these situations before the slopes are built. Batholith soils are usually well drained and low in silt content, except in or near draws where soils are deeper. These areas are where the problems occur.

When cut heights are very short on uniformly sloping sidehills, vertical slopes generally work well, as seen in figure 15. In situations that are obviously well drained, but when soil depths are fairly deep, they may still work satisfactorily, as seen in figure 16. For cuts steeper than 1:1 in some of the deeper, well-drained slopes structural stability may be retained, but sloughing can become a problem, especially whe cornice conditions begin to form at the interface of the cut and natural ground, as seen in figure 17. Figure 18 shows what can happen to cuts steeper than 1:1 in the deeper soils that are not as well drained. The crack seen in the picture is a planar failure that has resulted in a section of the cut slumping toward the road.

Use of vertical slopes for cuts of 6 feet (1.83 m) or less is still being debated. The design of cut slopes obviously is difficult and requires the use of all available information and skill. Seismic traverses were attempted in 1970 to help with the design but the material is generally such a heterogeneous mixture that the investigations were inconclusive and abandoned. Therefore, on-the-ground inspection and judgment had to be used.

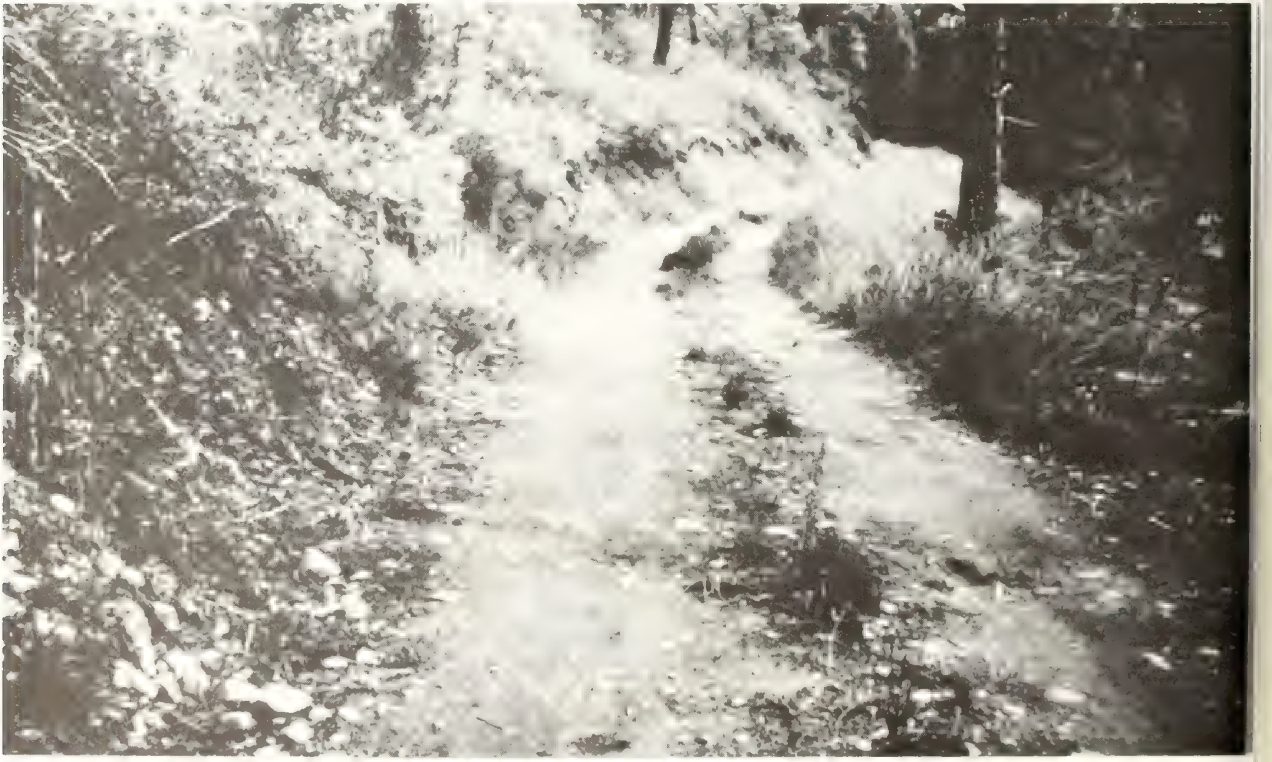
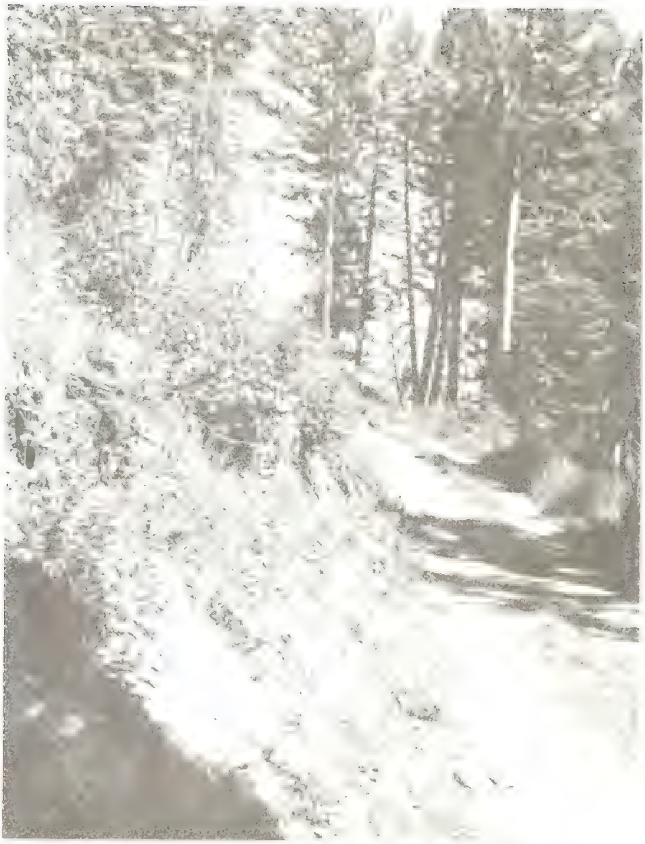


Figure 15.--Short, stable vertical backslopes on uniformly sloping terrain.

Figure 16.--Transition from 3/4:1 to vertical backslopes going away from the camera.



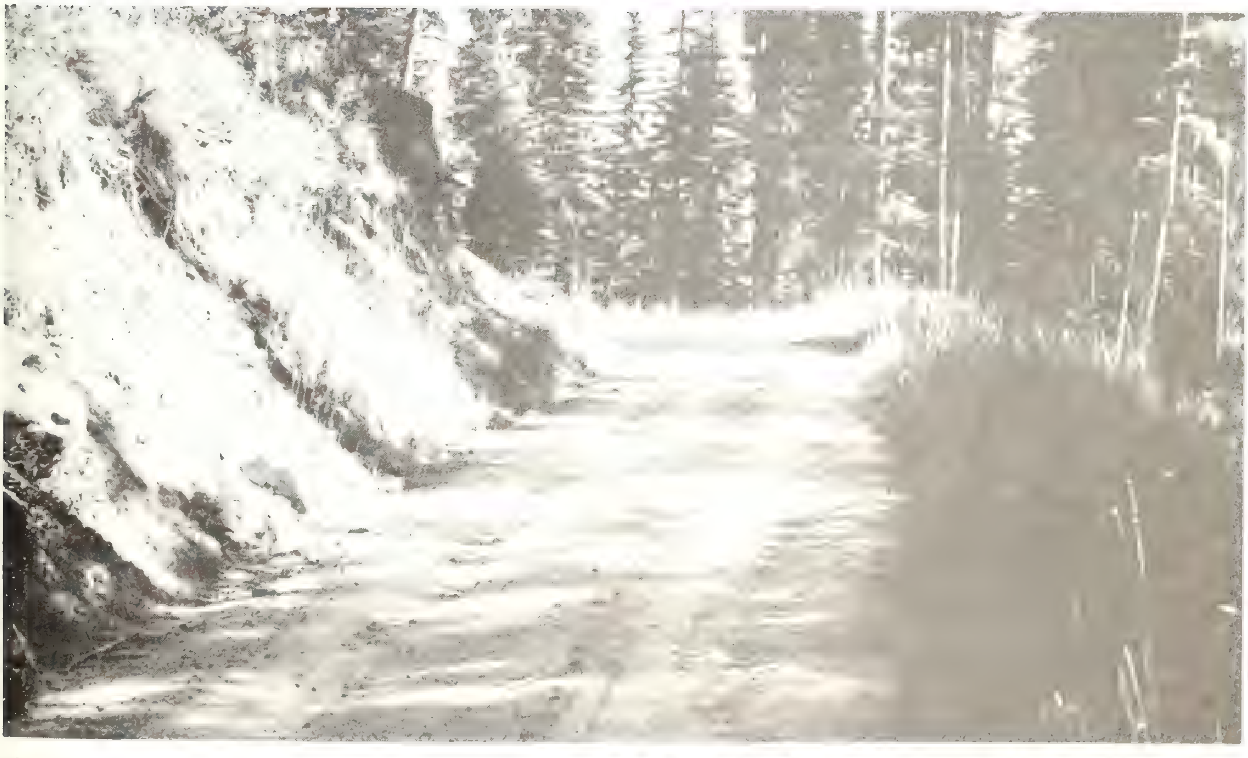


Figure 17.--Cut slope near maximum height of 6 feet (1.83 m)--structurally stable, but prone to sloughing. A cornice is beginning to build at the top of the cut.

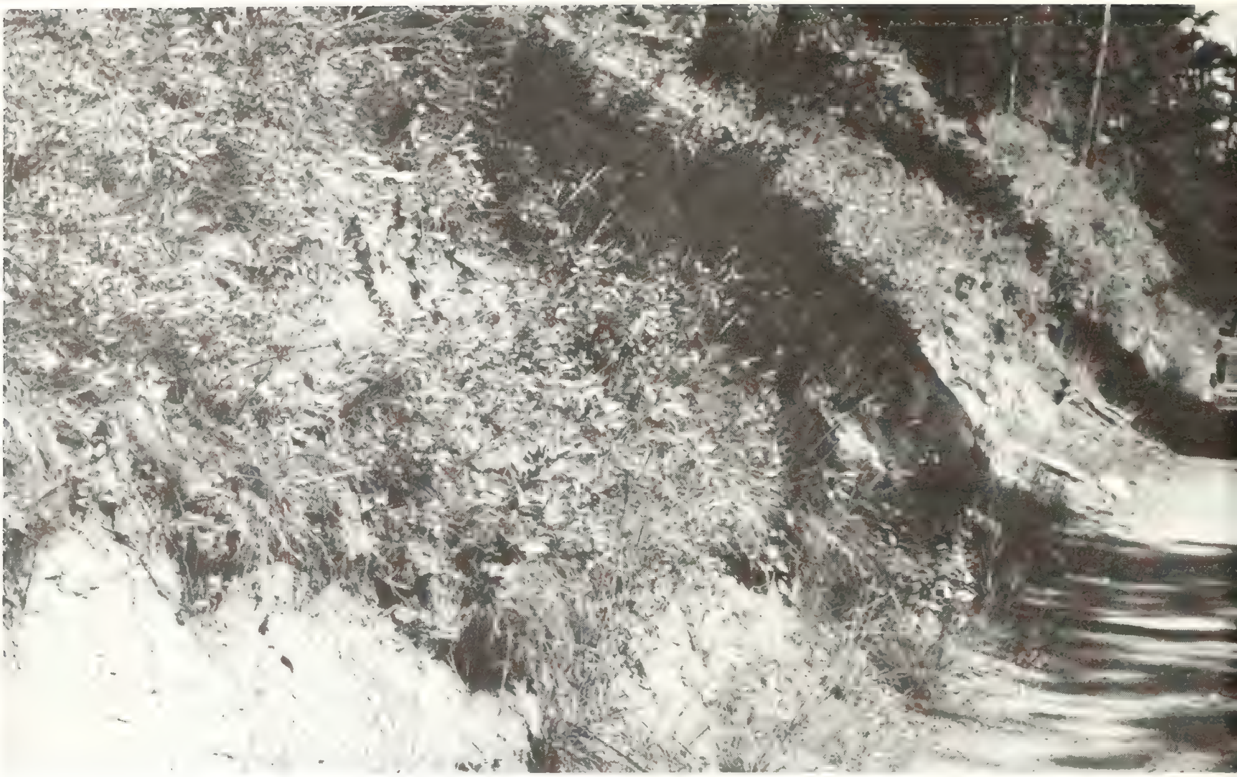


Figure 18.--Crack in a cut slope that is near the 6-foot (1.83-m) maximum height.

Culverts

Culverts were eliminated from minor draws. All culvert drainage is functioning satisfactorily on both sections.

Revegetation

No changes were made in revegetation, and the success was good for fill slopes on both sections. One of the disadvantages of vertical backslopes is that they cannot be seeded or planted. However, for the short slopes, natural vegetation usually invades from above as seen in figure 15.

CONCLUSIONS AND RECOMMENDATIONS

There is strong evidence that the effort to minimize environmental and esthetic impact produced good results. Although quantitative data are not available to give a better measure of the success, subjective evaluation of results leaves little doubt.

The discussion and photos in the preceding sections show quite conclusively that the road has produced little sedimentation and has maintained its basic integrity without any maintenance since its last use in 1971.

Strict adherence to the following principles will usually produce good results for reducing road impacts in the Batholith and elsewhere.

--Reduce road travel widths to the minimum needed to accommodate the traffic and other uses such as logging equipment.

--Contour and roll grades to disrupt natural drainage patterns as little as possible and reduce cut-and-fill slope heights. This will greatly reduce the potential for the buildup of waterflows.

--Carefully locate and design turnouts where the terrain is favorable to reduce overall impact of cuts and fills.

--Use dips where needed for cross drainage, but construct perpendicular to the traffic to reduce impacts on traffic use--also, construct dips along with the grading operation to control water during construction.

--Use insloping, outsloping, grade breaks, dips, and berm designs carefully and effectively as demonstrated to control water on single-lane roads without a ditch.

--Consider the use of slash as a barrier to sediment movement from fill slopes.

--Consider the use of reduced clearing widths to reduce the total area opened up by right-of-way clearing.

--Always revegetate the first year following construction to help stabilize the raw cut-and-fill slopes.

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utaries.

[illegible] by the Douglas-fir beetle and protect the residual stand.

KEYWORDS: road construction, design standards, fragile soils, erosion.

[illegible]
1978. Road design guidelines for the Idaho Batholith based on the China Glenn Road study. USDA For. Serv. Res. Pap. INT-204, [illegible]

[illegible] posed granitic soils of the Idaho Batholith resulted in a 1965 moratorium on road construction in the South Fork of the Salmon River and its tributaries.

In 1970, the China Glenn Road was built to salvage trees attacked by the Douglas-fir beetle and protect the residual stand.

KEYWORDS: road construction, design standards, fragile soils, erosion.

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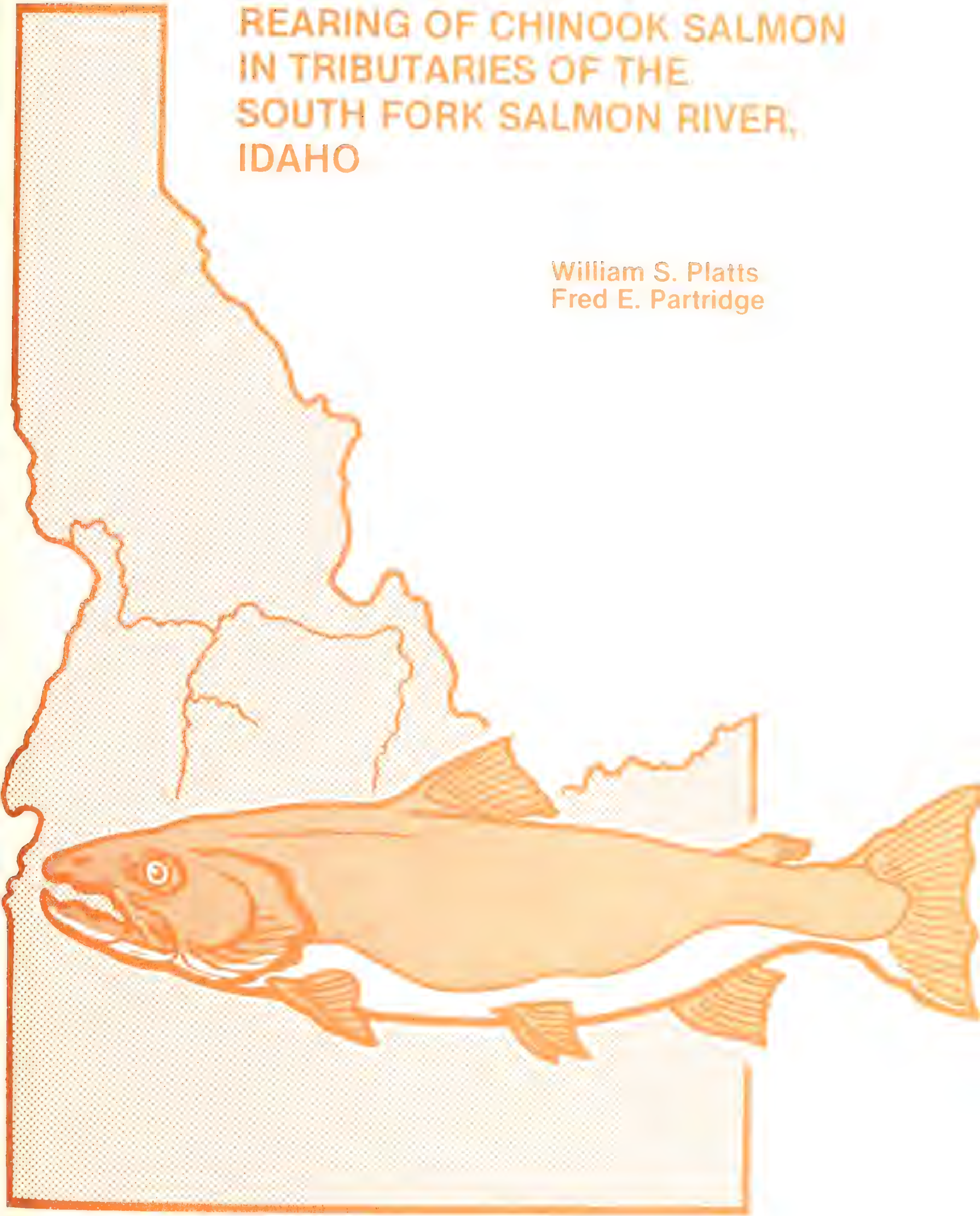
REARING OF CHINOOK SALMON IN TRIBUTARIES OF THE SOUTH FORK SALMON RIVER, IDAHO

William S. Platts
Fred E. Partridge



USDA Forest Service Research Paper INT-205
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

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May 1978

REARING OF CHINOOK SALMON IN TRIBUTARIES OF THE SOUTH FORK SALMON RIVER, IDAHO

William S. Platts and Fred E. Partridge

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

RESEARCH SUMMARY

Fish populations in 23 tributaries of the South Fork Salmon River were sampled in 1971, 1972, and 1974. Juvenile chinook salmon were found in one secondary and 11 primary tributaries. The first 400 m reach of stream adjacent to the river was the most important area for rearing and supported 58 percent of the total tributary chinook salmon population. Only three tributaries had chinook salmon more than 1.6 km from the river. The tributary chinook salmon standing crop ranged from 0.01 to 0.38/m^2 and averaged 0.06/m^2 for all streams.

Chinook salmon were rearing with rainbow trout and sculpin over most of their tributary range and occasionally with brook trout, Dolly Varden, mountain whitefish, mountain suckers, and dace. Cutthroat trout and chinook salmon were not found together. Chinook salmon preferred the larger, lower gradient, grassy-banked streams having deep pools. Chinook salmon were found in the fluvial and depositional landtype associations but mainly in the alluvial and alluvial fan landtypes.

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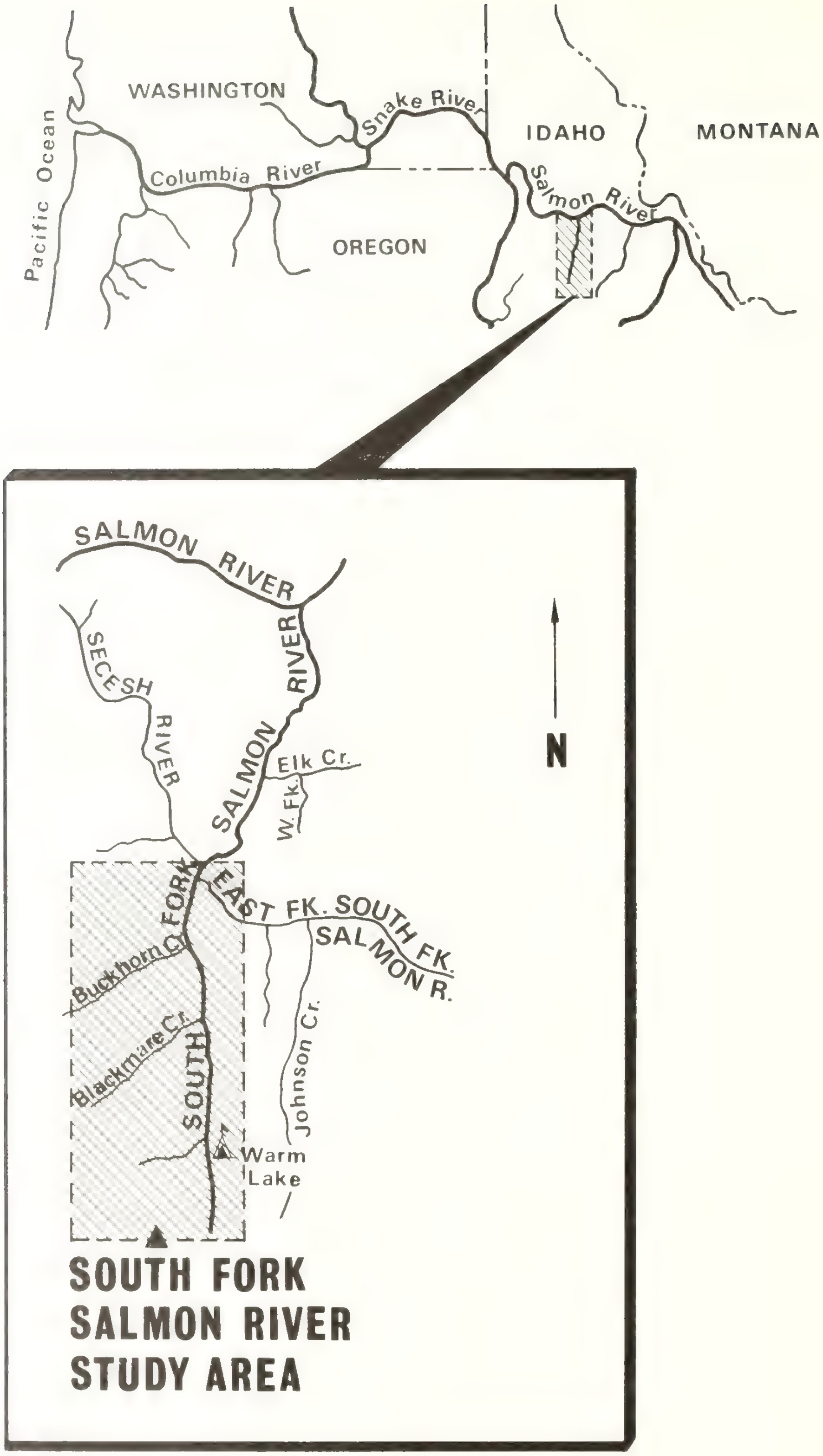

Figure 1.--A portion of the Columbia River drainage, showing the South Fork Salmon River and study area.

SALMON POPULATIONS IN THE SOUTH FORK DRAINAGE

Adult chinook salmon, *Oncorhynchus tshawytscha* (Walbaum),[1] and steelhead trout, *Salmo gairdneri* Richardson, returning from the ocean to the South Fork Salmon River (SFSR) have steadily declined in numbers since 1957. This decline resulted in sport fishing closures on both species. Summer chinook salmon are approaching the status of a "threatened species" in the Salmon River drainage. There is no evidence that their populations have stabilized or that the downward trend will not continue. Decline of salmon populations in the Salmon River Drainage has been caused mainly by impoundments in the lower Snake and Columbia Rivers. In the South Fork of the Salmon River, erosion triggered by past logging has probably contributed to the decline by silting and filling in sections of the streambed. If degraded habitat is to improve, land managers must be able to identify streams critical to summer chinook salmon survival.

Adult summer chinook salmon runs into the SFSR are monitored by the Idaho Fish and Game Department by conducting annual salmon redd counts. However, there is little knowledge of the status and needs of the juvenile stage of the summer chinook salmon's life cycle in the SFSR drainage. In the past it has been assumed that the rearing of salmon juveniles was almost entirely in the main SFSR. This report evaluates the use and importance of small tributaries for rearing summer chinook salmon.

SURVEY OF SOUTH FORK TRIBUTARIES

Study Sites and Methods

The SFSR is a major tributary of the Salmon River, draining a 1,270 mi^2 (3,290 km^2) watershed representative of much of the forested mountainous terrain found in central Idaho (fig. 1). The study area includes 397 mi^2 (1,028 km^2) of watershed along the upper 52 miles (84 km) of the river. The study area topography ranges in elevation from 9,000 feet (2,740 m) around the headwaters, to 3,700 feet (1,130 m) at the river's confluence with the East Fork-South Fork Salmon River. Most slopes are steeper than 40 percent and slopes more than 65 percent are common. Waters draining from the watershed are low in mineral content (averaging 60 mg/liter total dissolved solids) because of the dominant granitic bedrock in the watershed (Platts 1974).

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[1] Scientific names according to the American Fisheries Society (1970) list of common and scientific names of fishes.

The SFSR historically contained Idaho's largest salmon run, which is composed entirely of summer chinook salmon. This race has been reduced from more than 5,000 returning adults in the mid-1950's to about 700 returning adults in 1977. Almost all of the SFSR chinook salmon spawn in the river and a few spawn in the tributaries. Some juvenile chinook salmon hatched in the SFSR probably migrate into the tributaries to rear. Fish populations in the study tributaries are dominated by rainbow trout, *Salmo gairdneri* Richardson, followed by chinook salmon, Dolly Varden, *Salvelinus malma* (Walbaum), brook trout, *Salvelinus fontinalis* (Mitchell), sculpin, *Cottus* spp., cutthroat trout, *Salmo clarki* Richardson, mountain whitefish, *Prosopium williamsoni* (Girard), dace, *Rhinichthys* spp., and sucker, *Catostomus* spp.

The 23 tributaries, accounting for about 80 stream miles (130 stream km) were described for fish population structure by using an average of one 50-foot (15.2 m) study plot for every 465 yd (425 m) of stream. All streams were sampled randomly from mouth to headwaters until the stream became dry. Each study plot was selected with a table of random numbers, marked on aerial photographs (1-15,000), and then located on the ground. The plots were located 100 feet (30.5 m) upstream from the photographic location to avoid any bias resulting from the method of locating study plots.

Stream Environment

The aquatic survey used methods outlined by Herrington and Dunham (1967), with modifications (Platts 1974) to increase the validity in variable estimates and to quantify additional physical conditions. The methods satisfactorily quantified most of the variables, because water depths rarely exceeded 48 inches (122 cm) and water velocities were never excessive for wading. The clear water with low flows (July-November) offere excellent conditions for observational measurement.

A transect (channel cross section) was used to identify the stream reach where th aquatic structural analysis and fish population data would be taken. (A transect is a imaginary line running perpendicular to the centerline of the stream.) Each station included a cluster of five transects at 50-foot (15.2-m) intervals. The following measurements and conditions were recorded:

1. Stream, pool, and riffle widths.
2. Stream depths at equal intervals across the stream.
3. Ratings, locations, and features of pools.
4. Streambed material.
5. Cover, conditions, and types of streambanks.
6. Channel elevations and gradients.
7. Landtype association and landtypes.
8. Stream order.
9. Fish species and numbers.

A given transect crossing the stream channel was divided into 1-foot (0.3-m) inte vals, and the dominant streambed material was classified as follows:

Particle Diameter	*Classification*
12 inches or over (304.8 mm or over)	Boulder
3 to 11.99 inches (76.1 to 304.7 mm)	Rubble
0.185 to 2.99 inches (4.7 to 76.0 mm)	Gravel
0.184 inch and less (less than 4.7 mm)	Fine sediment

Stream areas were stratified as either pool or riffle. The pools then were classified as to suitability as fish environment as follows:

[illegible]	[illegible]
Maximum pool diameter exceeds average stream width. Pool is more than 3 feet (0.92 m) in depth, or more than 2 feet (0.6 m) deep with abundant fish cover.	5
Maximum pool diameter exceeds average stream width. Pool is less than 2 feet in depth, or if between 2 and 3 feet, lacks fish cover.	4
Maximum pool diameter is less than the average stream width. Pool is more than 2 feet in depth, with intermediate to abundant cover.	3
Maximum pool diameter is less than the average stream width. Pool is less than 2 feet in depth and has intermediate to abundant cover.	2
Maximum pool diameter is less than the average stream width. Pool is less than 2 feet in depth and is without cover.	1

Streambank type and condition were rated using the total streamside area between each transect, in accordance with the following tabulation. (Streamside type indicates habitat type where the transect met the bank.)

Vegetation		*Stability*		*Habitat Type*	
Forested	2.0	Excellent	2.0	Sod, root, log	2.0
Brush	1.5	Good	1.5	Brush, rubble	1.5
Grass	1.0	Fair	1.0	Grass, gravel	1.0
Exposed	0.5	Poor	0.5	Fines, road fill	0.5

Station and transect channel elevations were read with an altimeter; elevations were accurate to ±40 feet (12 m).

At each transect channel gradients were recorded with a clinometer, then averaged over each 200-foot (61-m) study section.

Stream width refers to surface water widths measured perpendicular to the flow. Station depths were averaged from four equidistant measurements.

Stream order was determined by methods originally developed by Horton (1945) and later modified by Strahler (1952, 1957); when two channel segments of order N join they then form a channel of order N+1.

Fish Collection Methods

The low concentration of total dissolved solids (60 mg/liter) in stream waters meant that more reliable fish population samples could be obtained with explosives than by using electrical fish collecting equipment. A total of 2.75 miles (4.42 km) of stream were sampled at 291 stations, using 4 miles (6.4 km) of explosive prima cord.

A 0.13- to 0.23-inch (0.33- to 0.58-cm) mesh net was stretched across the stream block fish from moving out of the sampling area prior to the explosion. The net and t effectiveness of prima cord assured an unbiased collection of close to 100 percent of the fish population within each sample area. All collected fish were identified and total length measured.

Fish in lower Lodgepole and Curtis Creeks were also collected with a Smith-Root type V electrofisher in 1974. The stream was stratified into 26-foot (7.9-m) sample sections. A net was used to block the downstream end of each study plot so fish could not escape downstream. Each reach was electrofished upstream and then back downstream

The upstream and downstream collections were kept separate and all fish identifie and measured. The two separate population numbers were then regressed to gain an estimated total population using the two-catch method described by Seber and Le Cren (1967).

These two streams were continuously electrofished to determine how fish community structure changed as distance from the river and channel elevation increased. Curtis and Lodgepole Creeks were electrofished completely from their mouths 1,144 yd (1,046 m and 1,733 yd (1,585 m) respectively upstream.

RESULTS OF TRIBUTARY SURVEY

Tributary Streams Used by Salmon

Summer chinook salmon, although considered primarily a river fish, utilize most c the tributaries in the upper 50 miles (80 km) of the SFSR for rearing and minor spawni Of the seven secondary and 16 primary tributary streams sampled for fish, one secondar and 11 primary streams contained chinook salmon (table 1). (Primary tributaries empty directly into the SFSR, while secondary tributaries empty into a primary tributary).

Chinook salmon could occur in other streams, but manmade blocks keep them out. Our random sample design could have caused us to miss some reaches containing chinook salmon. Tailholt Creek contains rainbow trout but no chinook salmon because a dam blocks this stream. The first sampling station on Four-Mile Creek was 0.5 mile (0.8 above the mouth and even though no chinook salmon were found in or upstream from this area it is possible they could rear downstream from this point. Both Cougar and Six- Creeks are relatively large tributaries and based on findings in adjacent tributaries were expected to rear chinook salmon. However, salmon were not found in any of the sample areas.

Stream Reaches Most Used by Salmon

Fifty-eight percent of the juvenile summer chinook salmon were rearing in stream reaches within 440 yd (400 m) of the river (table 2). In Tyndall, Trail, Dollar, Bla mare, and Fitsum Creeks, some of the larger streams in the study area, chinook salmon were found only in the first 440 yd (400 m) of stream. If stream size had been a dominant factor it would be expected that chinook salmon would rear further up these streams than they did.

Table 1.--*Fish species occurring in tributaries of the South Fork Salmon River*

Tributary	Chinook Salmon		Rainbow Trout	Cutthroat Trout	Dolly Varden	Brook Trout	Mountain Whitefish	Sculpin	Dace	Sucker
	<¼ Mi[1]	>¼ Mi[2]								
Bear	x	x	x		x	x		x		
Blackmare	x		x		x	x		x		
Buckhorn	x	x	x		x			x		x
West Fork			x	x						
North Fork			x	x	x					
South Fork					x					
Cabin	x	x	x		x	x	x	x	x	
Cougar			x		x	x		x		
Curtis	x	x	x		x	x	x	x		
Trail[3]	x		x	x	x	x		x		
Dollar	x		x			x		x		
Fitsum	x		x	x				x		x
Four-Mile				x						
South Fork				x	x					
Lick	x	x	x			x		x		
Cly[3]			x							
Duck Lake[3]				x						
Lodgepole	x	x	x		x	x		x		
Roaring	No fish found									
Six-Bit			x		x					
Tailholt			x							
Tyndall	x		x		x			x		
Upper SFSR	x	x	x		x		x	x		

[1] Ocurring ¼ mile or less above mouth of stream.
[2] Ocurring over ¼ mile above mouth of stream.
[3] Secondary tributaries.

Table 2.--*Stream reaches used by chinook salmon in relation to the river. Percent of total fish [illegible] stream is in parentheses*

	Reach distance from river (miles)											
	(0 - 0.25)		(0.25 - 0.5)		(0.5 - 0.75)		(0.75 - 1)		(1 - [illegible]		[illegible]	
	Salmon	%	*Salmon*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	*Salmon*	[illegible]	[illegible]	[illegible]
Bear	9	(90)	1	(10)								
Blackmare	39	(100)										
Buckhorn	0	(0)			[illegible]	[illegible]			[illegible]	[illegible]	3	(25)
Cabin	47	(54)	21	[illegible]	19	(22)						
Curtis (1971)	10	[illegible]	36	(24)	[illegible]	(34)	[illegible]	[illegible]	[illegible]	(30)		
(1974)[1]	101	(44)	55	(24)	72	(32)						
Dollar	2	(100)										
Fitsum	17	(100)										
Lick			[illegible]	(0)					12	[illegible]	[illegible]	(33)
Lodgepole (1971)	40	(98)	1	[illegible]								
(1974)[2]	209	(94)	[illegible]	[illegible]	1	(0.5)						
Trail	1	(100)										
Tyndall	22	(100)										
Total	497	(58)	126	(15)	146	(17)	[illegible]	[illegible]	64	(8)	[illegible]	[illegible]

[1] 0.65 mi of stream sampled.

[2] 1 mi of stream sampled.

Only three streams (Curtis, Buckhorn, and Lick Creeks) were found to have chinook salmon more than 1 mile (1.6 km) upstream from the mouth. These are all major tributa ies, with stream widths averaging more than 18 feet (5.5 m) and individual stream leng over 6.5 miles (10.4 km). Juvenile chinook salmon were not found in the main SFSR abo the confluence of Vulcan Hot Springs Creek, 7 miles (11 km) from the SFSR headwaters.

Random sampling of Lodgepole Creek in 1971 found 98 percent of the chinook salmon in the first 0.25 mile (0.4 km) of stream adjacent to the river and only 2 percent in the second quarter mile of stream. In 1974 the electrofishing results were comparable with 94 percent of the chinook salmon collected in the first quarter mile, 5 percent i the second quarter mile, and 1 percent in the third quarter mile of stream (fig. 2). However, in Curtis Creek in 1971 random sampling collected only 6 percent of the chino salmon in the first quarter mile of stream as compared to 44 percent collected in 1974 by elctrofishing (fig. 3). Chinook salmon were found about 1.2 miles (2 km) above the mouth in Curtis Creek.

Salmon Standing Crops

Standing crops of juvenile chinook salmon in the tributary streams averaged from 0.001 salmon/ft^2 (0.011/m^2) in Dollar Creek to 0.036/ft^2 (0.383/m^2) in Lodgepole Creek (table 3). Six streams (Tyndall, Lodgepole, Curtis, Cabin, Blackmare, and Fitsum Creeks) had standing crops averaging higher than 0.019/ft^2 (0.202/m^2). The remainder of streams had chinook salmon standing crops less than 0.006/ft^2 (0.068/m^2), with an overall average of 0.005 salmon/ft^2 (0.055/m^2).

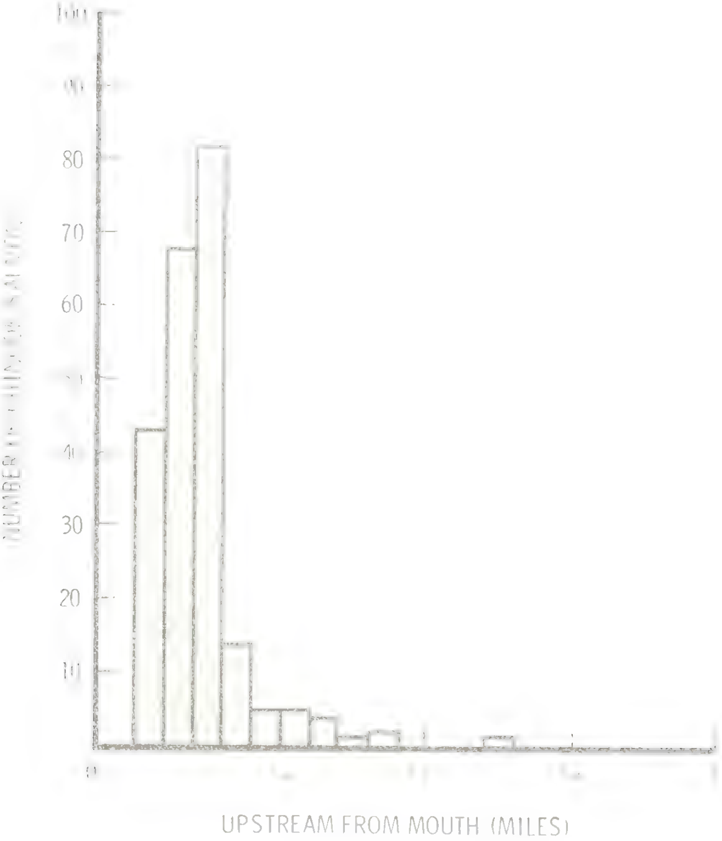
The extensive electrofishing of the lower reach of Lodgepole Creek in 1974 yielde a population estimate of only 0.006 chinook salmon/ft^2 (0.068/m^2). The higher standin crop in the 1971 random sampling could be due to the two lower stations being in highl populated reaches. The Curtis Creek standing crop estimate was 0.003/ft^2 (0.031/m^2). Sampling in Lodgepole Creek included the entire range of the juvenile chinook salmon rearing area in 1974 while the sampling in Curtis Creek only covered a part of their range.

Population estimates in September 1975 on Big Springs Creek, Idaho, found chinook salmon densities of 0.002/ft^2 (0.020/m^2)(Horner and Bjornn 1976). Horner and Bjornn also made visual (snorkeling) estimates of selected study sites on Bear Valley Creek i July 1975 and estimated less than 0.004 chinook salmon/ft^2 (0.04/m^2).

In Capehorn, Elk, and Marsh Creeks, tributaries of the Middle Fork Salmon River, chinook salmon densities averaged about 0.034/ft^2 (0.368/m^2) in August 1972 and 1973 (Bjornn and others 1974). The major portion of the chinook salmon were located in poc areas with depths over 0.5 foot (0.15 m). Edmundson (1967) visually (snorkeling) reported 0.020 chinook salmon ft^2 (0.220 per m^2)for a selected study site on Crooked Fork, a tributary of the Lochsa River.

The SFSR tributaries are considered marginal for rearing of summer chinook salmor and standing crop values were lower than in those areas considered prime salmon and steelhead rearing areas.

Figure 2.--Distribution of juvenile chinook salmon in the first mile of Lodgepole Creek, 1974.



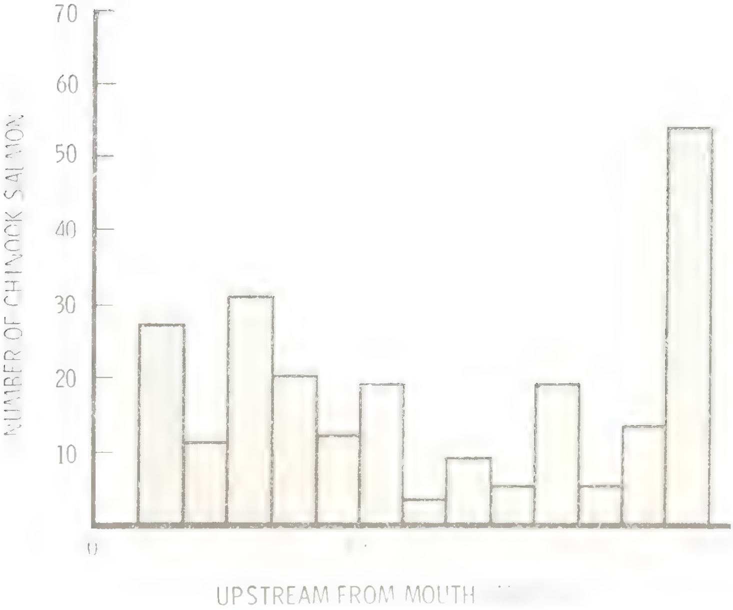


Figure 3.--Distribution of juvenile chinook salmon in the first two-thirds mile of Curtis Creek, 1974.

Table 3.--*The standing crop of the chinook salmon in tributaries of the South Fork Salmon River*

Stream	Stream area sampled	Number of salmon	Salmon per ft^2
	ft^2		
Dollar	1,900	2	0.001
Buckhorn	6,500	12	.002
Trail	500	1	.002
Lick	6,500	18	.003
Curtis[1]	85,800	[2]251 ± 19	.003
Bear	2,000	10	.005
Upper SFSR	1,500	9	.006
Lodgepole[1]	45,630	[2]288 ± 53	.006
Cabin	4,625	87	.019
Curtis	8,000	152	.019
Fitsum	750	17	.023
Tyndall	925	22	.024
Blackmare	1,350	39	.029
Lodgepole	1,150	41	.036

[1] Complete sampling of the lower reach only (1974), all other streams were randomly sampled (1971, 1972).

[2] Estimated populations, 95 percent confidence limit.

ECOLOGICAL RELATIONSHIPS

Salmon in the Community Structure

Rainbow trout, possibly composed mainly of juvenile steelhead trout, were found i all stream areas occupied by chinook salmon (table 4). Steelhead trout are using all tributary areas for spawning and rearing that chinook salmon are using plus upstream areas chinook salmon are not using. Rainbow trout were dominant over chinook salmon i the tributaries, making up 44 percent of the total population, while chinook salmon ma up 32 percent.

Numbers of adult chinook salmon and steelhead trout migrating into the SFSR were low during the years of study compared to past years (Hoss and others 1975; U.S. Army Corps Engineers 1963-1976). Even if chinook salmon and steelhead trout numbers were a high as they were in the mid-1950's, the ratio between the two species would probably b similar. If adult runs into the SFSR of one species should start increasing over the other species, changes should show in the juvenile standing crop ratio.

Sculpin were found in all of the tributary streams and all but one of the tributa areas used by chinook salmon. Both species prefer low energy habitats with relatively low channel gradient. Brook trout and chinook salmon were found living together in three streams. Cutthroat trout, which were only found in upper stream reaches, were r

Table 4. [illegible]

Species	Alone	Rainbow	Chinook salmon	Sculpin	Dolly Varden	Eastern brook	Cutthroat	Mountain whitefish	Dace	Sucker
Rainbow	12		1	10			1		1	
Chinook salmon	0	12		11	[illegible]		0		1	2
Sculpin	1	10	11				[illegible]	[illegible]	1	1
Dolly Varden	13	3	2					[illegible]	0	0
Eastern brook	[illegible]	5	5	[illegible]	[illegible]		0	1	1	[illegible]
Cutthroat	[illegible]	4	0	0	[illegible]	1		[illegible]	[illegible]	0
Mountain whitefish	0	3	[illegible]	2	0	1	[illegible]		1	0
Dace	0	1	1	1	0	1	0	1		[illegible]
Sucker	0	2	1	1	0		0	[illegible]	[illegible]	

found with chinook salmon. Chinook salmon were found with Dolly Varden, mountain whitefish, and mountain suckers in only two streams, and with dace in Cabin Creek, the only stream containing dace. Finding chinook salmon in Cabin Creek was unexpected because it was believed that the Cabin Creek culverts were impassable to migrating adult salmon and steelhead trout.

The standing crop information demonstrates the controlling effect that anadromous fish can have on resident fish. If chinook salmon and steelhead trout populations disappeared from the SFSR, the lower reaches of the tributaries would undoubtedly be used more by resident trout species.

Salmon Densities Related to Aquatic Habitat Conditions

Juvenile chinook salmon preferred stream areas containing high quality pools, with 55 percent occurring in pools with excellent ratings (Platts 1974). Pool condition accounted for 8 percent of the chinook salmon's observed variation in population numbers. However, even though chinook salmon preferred high quality pools, 59 percent were found in stream areas where the percent of channel in pool was less than 20 percent. This can be explained by chinook salmon preferring lower tributary reaches that naturally had a low pool/riffle ratio. Seventy-one percent of the chinook salmon collected were in stream reaches with widths more than 30 feet (9.1 m).

As average channel gradients increased from 2 to 4 percent, mean chinook salmon numbers per stream length increased. As channel gradients increased above 4 percent, chinook salmon numbers declined and were not found in channels exceeding 10 percent gradient.

Chinook salmon in the study area reared in channels with elevations between 3,600 and 5,600 feet (1,100 and 1,710 m), with 52 percent occurring between 4,800 and 5,200 feet (1,460 and 1,580 m). These channel elevations corresponded to most of the tributary confluences with the SFSR.

Sixty-one percent of the chinook salmon collected were in channels dominated by grassy streambanks. The lowest densities found were in channels dominated by forested streambanks because chinook salmon reared mainly in the lower elevations where grassy streambanks dominate. The stability of the streambank and the composition of channel materials had no detectable influence on population means of chinook salmon. Chinook salmon were found in third, fourth, and fifth order streams, with their numbers increasing as the stream order increased. Fifth order streams contained 76 percent of the chinook salmon collected. Chinook salmon occurrence was influenced most by the proximity of the stream reach to the river.

Salmon Occurrences as Related to Geomorphic Type

Chinook salmon were found in six landtypes within two of the four landtype associations (fluvial and depositional) occurring in the study area. Fluvial lands are lands formed by the erosive force of running water. Depositional lands are formed by water and glacial soil deposits. No chinook salmon were collected in the cryic landtype association, nor in the flaciated landtype association almost barren of fish, with only rainbow trout being found in the glacial trough landtype.

Chinook salmon dominated the fish populations in the alluvial and alluvial fan landtypes, and their populations occurred mainly in these low channel gradient areas in close proximity to the river. Chinook salmon were also found in streams within the moraine, dissected mountain slope, terrace, and valley train landtypes.

SUMMARY

Juvenile summer chinook salmon made unexpected use of the tributary streams; they were found in 69 percent of the tributaries sampled. They were the second most numerous fish species, following the resident and anadromous forms of rainbow trout, which were usually found living with chinook salmon.

Sculpin were found with chinook salmon in all but two tributary areas; and brook trout, Dolly Varden, mountain whitefish, sucker, and dace were occasionally found in the same stream areas.

Chinook salmon preferred high quality pools found in the larger streams, with lower channel gradients and grassy streambanks. They were most numerous in channel elevations between 4,800 and 5,200 feet (1,460 and 1,580 m). Chinook salmon were found mostly in the alluvial and alluvial fan landtypes, with the closeness of the stream reach to the river as the most important variable determining whether chinook salmon occurred or not.

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1978. Rearing of chinook salmon in tributaries of the South Fork Salmon River, Idaho. USDA For. Serv. Res. Pap. INT-205, 11 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Fish populations in 23 tributaries of the South Fork Salmon River were sampled in 1971, 1972, and 1974. Juvenile chinook salmon were found in one secondary and 11 primary tributaries. The first 100 m reach of stream adjacent to the river was the most important area for rearing and supported 58 percent of the total tributary chinook salmon population. Only three tributaries had chinook salmon more than 1.6 km from the river. The tributary chinook salmon standing crop ranged from 0.01 to 0.38 m^2 and averaged 0.06 m^2 for all streams.

KEYWORDS: chinook salmon, salmon habitat, trout, fisheries, management.

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PREDICTING SLASH DEPTH FOR FIRE MODELING

Frank A. Albini
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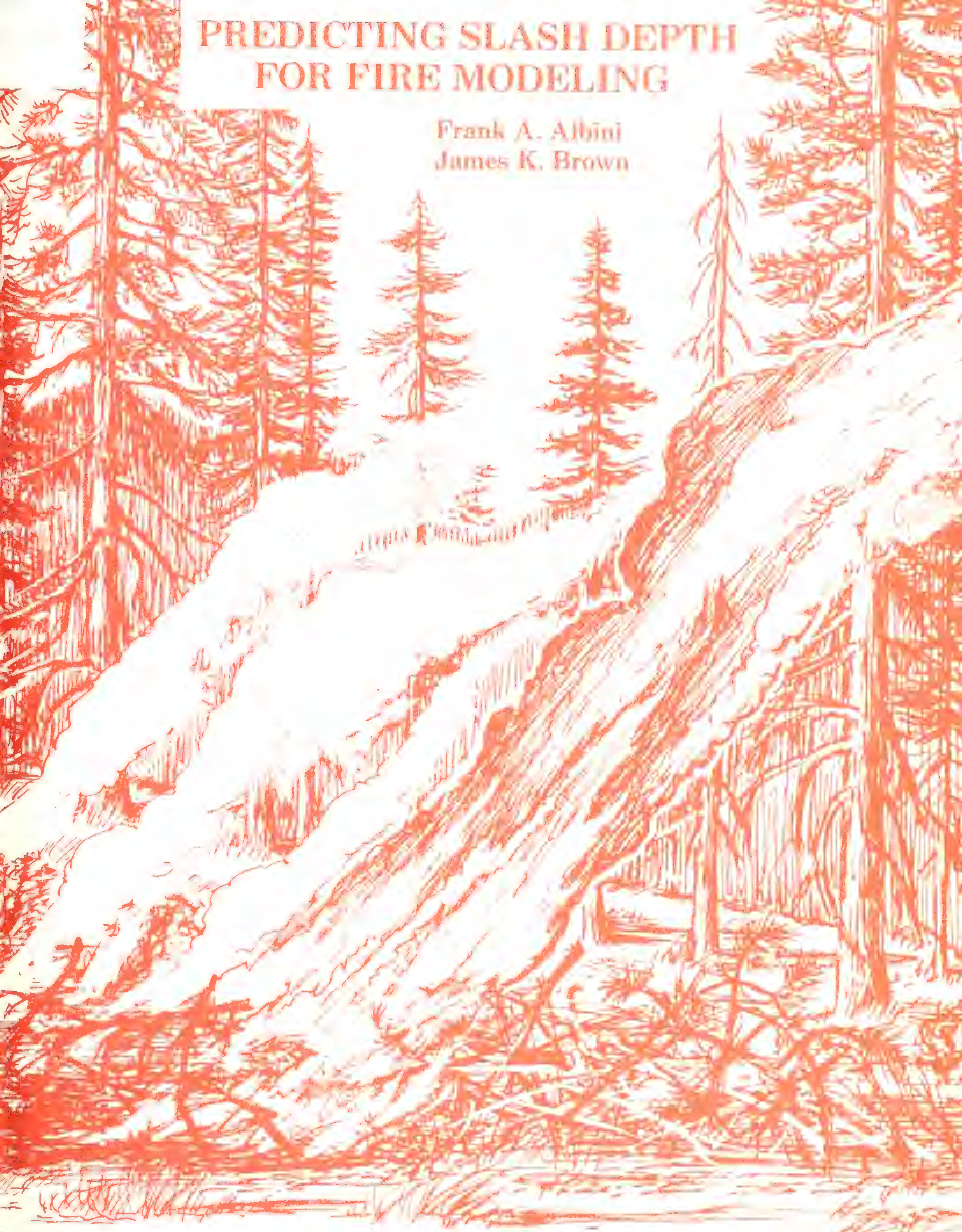

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PREDICTING SLASH DEPTH FOR FIRE MODELING

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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RESEARCH SUMMARY

Development of equations for predicting fuel bed depth (called "bulk depth" herein) appropriate for modeling fire behavior in slash is described. Bulk depth (y) was correlated with the expected number of 1/4- to 1-inch-diameter particle intercepts per foot of vertical plane transect (x) by regressions of the form $y = a\sqrt{x}$. Values of "a" suitable for use in fire models were 0.767 for high-lead harvest debris, 0.940 for precommercial thinning of pines, 1.22 for precommercial thinning in several other western conifers, 0.877 for ground-lead harvest debris in pines, and 0.542 for ground-lead harvest in other species. Lopping of slash reduced average depth 17 percent for harvest debris and 31 percent for precommercial thinning debris. Correlation of high intercept depth (maximum height of sampled fuel particles) with bulk depth showed that the bulk depth can be well predicted using 64 percent of the more easily measured high intercept depth.

Models for settling of slash, retention of foliage and fine twigs, and species mixing, useful in preparing data for fire models, are presented. Application of the models in a slash hazard appraisal computer program is illustrated.

INTRODUCTION

Slash or debris created by harvesting and thinning are a major fire management problem because these residues can create unacceptable fire behavior hazards. Treating slash to maintain an acceptable fire hazard is expensive and requires skillful decision-making. An inexpensive, simple-to-use, yet objective means of appraising the potential fire behavior of slash is needed to aid decisions in managing slash. Knowledge of potential fire behavior can help determine treatment alternatives, the financing of slash treatment activities, and even determine whether the slash should be created. This report describes a method for predicting depth of slash fuels for analytical modeling of fire behavior.

The capability to predict debris and to model fire behavior has made possible a quantitative system for appraising fire behavior potential. Rate of fire spread and flame front intensity can be mathematically modeled using Rothermel's (1972) fire model, which is the basis for computing spread and energy release indexes in the National Fire-Danger Rating System (NFDRS). An area-growth-rate model by Anderson,[1] crown scorch model by Van Wagner (1973), and flame length models by Byram (1959) and Thomas (1962) are also available. A method for assessing total heat release and period of flaming that incorporates large-diameter fuels has been theorized by Albini.[2] The fire models require fuel loading by size class and fuel bed depth as inputs.

Loading and depth of debris vary considerably by cutting prescriptions, therefore must be estimated for each individual cutting situation. Other fuel inputs such as particle density, heat content, silica-free ash content, and particle surface area-to-volume ratio tend to be species dependent and can be approximated from known values (Albini 1976; Brown 1970b, 1974).

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[1] Office memo of August 10, 1973, on file at the Northern Forest Fire Laboratory, Missoula, Montana. (Manuscript in preparation by Hal E. Anderson.)

[2] Albini (1976) outlines the total heat load computation; the computation of burning time is based on empirical work reported by Harmathy (1972) describing structure fires and pile burning, modified slightly to agree with single-particle burning times reported by Anderson (1969).

For Rocky Mountain conifers, loadings of slash can be predicted from relationshi between tree crown weight and tree characteristics such as d.b.h. and height (Brown 1 In the USDA Forest Service Northern Region these relationships have been installed in computer program that obtains input from tree inventories and predicts potential debr as output.[3,4] In addition to predicting debris, a method to predict fuel depth is ne to appraise fire potential. The objectives of this study were:

1. Determine the relationship between fuel depth and loading of slash and the extent to which species, age of slash, method of skidding, lopping, and other factors influence the relationships.

2. Determine the relationships between the easily measured high intercept depth and bulk depth.

When using analytical models such as Rothermel's (1972), fuel depth is a critica parameter because it determines bulk density of the fuel array for given fuel loading Rate of fire spread is very sensitive to bulk density (Williams 1977). Fuel depth is measure of the vertical extent of fuel in the zone that is actively involved in the spreading flame front. Conceptually, the bottom of this zone is the forest floor and the top is the height where fuel ceases to exist or is too sparse to affect propagati of the flame front. Fuel depth that is compatible with fire modeling can be difficul to measure because locating the top of this hypothetical zone in the fuel array requi judgment.

Fuel depth in slash and other downed woody material has been measured primarily a high intercept basis (Brown 1974). In this procedure, the top of the fuel is defin by the highest particle to intersect a vertical plane about 1 foot wide. Although th procedure is easy to learn and to use, it does include large void spaces in the fuel array whenever they occur. This permits overestimation of an effective fuel depth an underestimation of bulk density required for fire modeling. A procedure for measurin effective fuel depth--called "bulk depth"--has been developed by William Frandsen (19 at the Northern Forest Fire Laboratory. It allows observers to account for void spac in the fuel arrays and provides a measure of effective fuel depth appropriate for fir modeling.

The merchantable top diameter relates to depth. Small top diameters result in m lopping of supporting branches and removal of bolewood than large top diameters; henc the slash is more compacted. Species may influence depth of slash due to differences in branch stiffness and branching habit. In a study by Roussopoulos and Johnson (197 loading and depth of slash were directly related; however, as loading increased, dept increased at a reduced rate. Probably as more tree crowns are added to a fixed area, overlapping of branches occurs and the weight may cause compression. Methods of fell and skidding trees should influence depth because the amount of trampling and breaka depends on if and how merchantable boles are removed.

Settling with age has a most significant influence on slash depth. For some western conifers over a 5-year period, depth of lopped and unlopped slash was reduce to one-half of the original value (Fahnestock and Dieterich 1962; Kiil 1968). Rate settling varied; for some species, depth actually increased slightly during the secor year before settling. In a study of piled slash over a period of 29 years, Wagener and Offord (1972) found that piles continued to settle; however, 50 percent of the settling occurred during the first 5 years.

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[3] Users' guide to debris prediction and slash hazard appraisal. 1977. USDA Fore Service Northern Region, Division of Fire Management, Missoula, Mont.

[4] Brown, James K., and Cameron M. Johnston. 1976. Debris prediction system. Of report on file at the Northern Forest Fire Laboratory, Drawer G, Missoula, Mont.

METHODS

Fieldwork

Sampling design.--The study was designed to provide data for four different skidding methods:

1. *Ground lead.*--Crawler tractor and rubber-tired skidder, entire log dragged.
2. *Skyline.*--One end of log elevated.
3. *Helicopter.*--Limited skidding.
4. *Precommercial thinning.*--No skidding.

For each skidding method, two species groups were desired and for each species group, two age classes of slash. For each combination of skidding method, species, and age, we attempted to locate two study sites on areas represented by each of three average loading levels: low (sparsely distributed), medium (nominally about half of ground covered by slash), and heavy (uniformly distributed).

Study sites were located in areas having different loadings to assure that any differences in skidding patterns due to loading would be reflected in the data.

Species were partitioned into the following two groups, based on similarity of lopped depths as observed by Fahnestock and Dieterich (1962):

1. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)
   Grand fir (*Abies grandis* (Dougl.) Lindl.)
   Alpine fir (*Abies lasiocarpa* (Hook.) Nutt.)
   Western redcedar (*Thuja plicata* Donn)
   Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)
   Western larch (*Larix occidentalis* Nutt.)
   Engelmann spruce (*Picea engelmannii* Parry)

2. Lodgepole pine (*Pinus contorta* Dougl.)
   Ponderosa pine (*Pinus ponderosa* Laws.)
   Western white pine (*Pinus monticola* Dougl.)

All slash was at least one-half year old and had existed through at least part of a winter. Two age classes were recognized: 0- to 1-year and 3- to 4-year. Some combinations of skidding, species, and age were not found. Because skyline and helicopter logging has received substantial use only recently in the Intermountain area, the 0- to 1-year and 3- to 4-year lodgepole pine and 3- to 4-year Douglas-fir were unavailable for sampling. Surprisingly, 0- to 1-year precommercially thinned stands other than pines were also unavailable. All other skidding, species, and age combinations were sampled.

Within study areas that were a minimum of several acres in size, two primary transects were established. Along each primary transect, a total of 50 or more sampling points were located at 2-foot intervals. Points without slash were not sampled.

Loading measurements.--Using the planar intersect technique (Brown 1974; Brown and Roussopoulos 1974), loading was measured for at least 15 randomly preselected sample points along each primary transect. Sometimes the random selection resulted in more than 15 points out of 50 for measurement of loading. For 1/4- to 1-inch particles, two 2-foot planes, crossed perpendicularly, were vertically oriented and intersections counted. For 1- to 3-inch and greater than 3-inch pieces, the 2-foot planes were extended to 4 feet. Particles 0 to 1/4 inch were not tallied because of the counting worl involved and the fact that the information appeared unnecessary to meet objectives.

Depth measurements.--High intercept and bulk depth measurements were recorded at each sampling point. High intercept depth was measured as the vertical distance from the bottom of the litter layer to the highest 0- to 3-inch diameter slash particle intersecting each 2-foot plane. Pieces greater than 3 inches in diameter were omitted in determining depth because they occur infrequently as the highest particle and have considerably less influence on rate of spread than smaller pieces.

Bulk depth was measured in each of four pie-shaped quadrants of a 2-foot diameter cylinder whose central axis was vertically oriented at each sample point. The two perpendicular sampling planes for tallying intersections of 1- to 3-inch particles, delineated the cylinder into quadrants. The top of fuel was the average height of an imaginary pliable sheet draped over the fuel particles. The bottom was at the base of the litter layer. Vertical gaps free of fuel for more than 1 foot were subtracted from each quadrant's depth. Gaps of less than 1 foot were assumed to maintain vertical continuity of flames, thus were included in the depth measurements. Depths of the four quadrants were averaged to obtain a bulk depth estimate for each sample point.

Lopping.--After loading and depth were measured initially, the slash along the transect was lopped so that all branches were within 2 feet of the ground and boles within 1 foot. High intercept and bulk depths were remeasured at all sample points where depth had changed.

Analysis

Rationale

To understand the rationale behind the method of analysis applied here, bear in mind the objectives of the effort and the nature of the variables. The first objective was to establish an equation that can be used to predict the mean bulk depth of a slash fuel bed from quantities that describe the amount of slash on the area. The sampling procedure provided an estimate of the bulk depth and the variables for quantifying the slash loading at each sample point: the number of intercepts of 1/4- to 1-inch and 1- to 3-inch-diameter fuel particles. The *expected* number of such intercepts can be predicted from slash loading, tree species, and d.b.h. simply by parsing the loading according to the fractional weight distribution of the individual tree crowns (Brown 1978). But the number of intercepts (regardless of size class) is subject to great sampling variability, since it should be approximately Poisson distributed.

A Poisson-distributed variable has a variance equal to its mean, so if N is its expected value, samples from $N - \sqrt{N}$ through $N + \sqrt{N}$ should occur with approximately equa frequency. This intrinsic variability makes it impossible to distinguish with certaint between a change in the mean value of the number of intercepts and simple data scatter when moving from one sample point to the next. To alleviate this problem, the data can be aggregated, combining measurements that lie within a range $\pm\sqrt{N}$ of each other. We ca use the average values to discern the underlying trend of the average bulk depth with the average number of intercepts; otherwise, the trend would be largely obscured due to the great scatter in the individual samples. Sampled bulk depths also exhibited significant scatter, indicating a need to aggregate data.

Fuel bed depth was related to the [illegible] iameter fuel particles per foot of planar intersect by fitting regressions through ggregated data points. The 1/4- to 1-inch particles served as a proxy for the loading f debris fuel under 3 inches in diameter. The fitting of data points resulted from a hree-step averaging process as described below:

1. For each study area, the data from the two transects were treated as a single et. Only sample points at which intercepts were counted were assembled in the data et, so the "unit" of sample information consisted of a triplet of numbers--the bulk epth, in inches; the total numbers of intercepts of 1/4- to 1-inch size class fuels in he two crossed sample planes; and the number of intercepts of 1- to 3-inch size class uels in the same two (extended) planes.

For inspecting these triplets of numbers, they were aggregated and displayed in ive categories, according to the number of 1/4- to 1-inch intercepts: 0-2, 3-6, 7-13, 4-22, and 23 or more intercepts. The display (table 1) consisted of the following escriptors for each subset:

- a. Average bulk depth
- b. Average 1/4- to 1-inch intercept count
- c. Number of sample triplets in the subset
- d. Mean square bulk depth
- e. Mean square 1/4- to 1-inch intercept count.

Scrutiny of such tables quickly revealed sample points that were obviously not representative, so they could be culled from the data set. The mean square depth figures erved well to permit the "outlaw" points to be identified. Fewer than 10 points were iscarded from more than 1,500 collected.

2. These data were analyzed in many ways in attempting to discover trends and orrelations. One fact that soon became evident was that no substantial dependence of ulk depth on the 1- to 3-intercept count could be established, whether or not the 1/4- o 1-intercept count was included. This allowed further simplification by combining ata for all 1- to 3-intercept counts. Table 2 displays this simplified data aggregaion. An asterisk indicates that a sample point has been discarded in computing the verages shown and two asterisks indicate the discarding of two data points. These data orm the basis for the regression relationships between bulk depth and number of 1/4- to -inch intercepts.

3. Data in table 2 were grouped by combinations of skidding method, species, and ge of slash. Constrained regressions were applied to the data because logically if no /4- to 1-inch fuel particles exist there should be no bulk depth. Analysis using unonstrained regressions supported this approach in that the constant terms were small nd often statistically nonsignificant.

In deriving the regression equations, the data from all units aggregated were veraged. That is, all the bulk depth-intercept count pairs in the intercept count ange 0-2 were averaged, all those in the range 3-6 were averaged, etc. Then the reressions were formed by weighting each resultant aggregate data point by the number f its supporting measurements.

Scatter diagrams of these "grand average" points showed a fraction power law form, o we chose to regress the average bulk depth against the square root of the average umber of 1/4- to 1-inch intercepts.

Table 1.--*Sample table of aggregated data from one area used for establishing the relationships between bulk depth and number of particle intersections*

1/4 to 1 intercept count range		Count of intercepts (total) in two crossed 2-foot planes, in 1- to 3-inch diameter size class							
		0	1	2	3	4	5	6	7
0-2	avg. depth	1.433	1.500	2.367	0.	0.	0.	0.	0.
0-2	avg. xcpts	1.333	.500	1.667	0.	0.	0.	0.	0.
0-2	No. points	3	2	3	0	0	0	0	0
0-2	msq depth	2.230	2.500	6.710	0.	0.	0.	0.	0.
0-2	msq xcpts	2.000	.500	3.000	0.	0.	0.	0.	0.
3-6	avg. depth	7.475	1.867	3.050	9.900	0.	0.	0.	0.
3-6	avg. xcpts	4.750	3.667	4.500	4.500	0.	0.	0.	0.
3-6	No. points	4	3	2	2	0	0	0	0
3-6	msq depth	99.57	4.127	9.365	102.4	0.	0.	0.	0.
3-6	msq xcpts	23.75	14.33	22.50	22.50	0.	0.	0.	0.
7-13	avg. depth	4.050	4.833	4.075	3.300	3.433	0.	0.	8.000
7-13	avg. xcpts	10.00	9.333	9.000	12.00	7.667	0.	0.	12.00
7-13	No. points	2	3	4	1	3	0	0	1
7-13	msq depth	21.47	27.08	18.60	10.89	18.43	0.	0.	64.00
7-13	msq xcpts	109.0	91.33	83.50	144.0	59.00	0.	0.	144.0
14-22	avg. depth	0.	6.800	7.150	6.000	0.	0.	0.	0.
14-22	avg. xcpts	0.	15.00	15.00	16.00	0.	0.	0.	0.
14-22	No. points	0	1	2	1	0	0	0	0
14-22	msq depth	0.	46.24	55.75	36.00	0.	0.	0.	0.
14-22	msq xcpts	0.	225.0	225.0	256.0	0.	0.	0.	0.
23+	avg. depth	0.	0.	0.	0.	0.	0.	0.	0.
23+	avg. xcpts	0.	0.	0.	0.	0.	0.	0.	0.
23+	No. points	0	0	0	0	0	0	0	0
23+	msq depth	0.	0.	0.	0.	0.	0.	0.	0.
23+	msq xcpts	0.	0.	0.	0.	0.	0.	0.	0.

11 ..--

it ber																		
5- [illegible]		[illegible]	[illegible]	[illegible]		4.36	5.58											
5-12		1.33	[illegible]	[illegible]		4.45	5.03									[illegible]	[illegible]	
5-13																51.75		
5-14		.67															16.30	[illegible]
5- [illegible]		1.25	[illegible]	[illegible]		4.11												
5- [illegible]																		
5- [illegible]																4.00	15.08	[illegible]
5-10							6.40											
5-12							2.00											
5- 3	*	1.00	2.64	8.82	12	4.33												
5- [illegible]		2.00	3.40	12.77		5.00	1.25										.00	841.0
5-23		1.[illegible]	1.92	6.32		5.00	3.56			8.46								
5-24	*	1.54	4.56	28.41		4.57	7.33											
5-25		.67	[illegible]	4.75		4.63	6.72			8.36								
5-26		1.33	4.27		22	4.82	8.08											
6-3		...	1.80	4.05	11	4.18	2.70											
6-4		1.00		6.49	11	4.08	5.62											
76-23		1.71	[illegible]			4.41												
76-24	3	1.[illegible]	4.38			4.80	7.23					154.						
76-30			1.50									285.		481.0				
75-15		1.67	2.27	7.25	6	4.17	3.57	14										
75-16		2.00	3.20	10.86		4.80		208	18	9.85	14.62	604.6	1[illegible].02					
75-17	10	...	[illegible]	81.87		4.56	6.85	75	12			201.2					.8	
75-18	1	1.00	[illegible]	[illegible]		[illegible]	17.42	336.	17		22.56	616.5	22.03					
76-10		1.20	3.88	[illegible]		4.75				7.38	7.62	68.0			1	27.0		81.
76-12		1.50	1.30		10	4.20		29		9.33			1[illegible].81	202.7			53.0	
76-13		1.40	[illegible]	22.21		4.40					7.82	71.6	13.70					
76-15		1.67	3.63			4.44	4.86				11.25	253.7						
76-16	4	1.75	5.98	47.02		4.65		117		9.51		278.4						
76- 1	11	1.27	3.65	18.80	9		11.01			8.58	18.21	127.8						
76- 5	11	1.18	[illegible]	34.83		4.50	13.30	227										
76- 6	1	2.00	9.50	[illegible]	10	5.00	12.03		20	9.80		44.7						
-17	13	1.08	4.16	24.86	11	4.09	8.10			8.67	10.91							
5- 4		.50	[illegible]	157.3	6	3.83		241.		9.20	14.41							
-19	1	2.00	5.00							10.23		242.8						
5-22	12	1.42	1.88				3.33		1	7.75		69.3						
- 3	14	1.43	[illegible]	15.30			8.23	107.	6		15.37							
-27	2*	1.43	5.40	45.97	11	4.36	13.64	200.			17.04	550.6						
-28		2.00	5.80	34.64		5.20	17.72		14			594.8	26.73					
-29	[illegible]*	1.12	5.83	42.20	11	4.45		62										
-31	[illegible]*	1.17	[illegible]		17	3.88												
										GAME								
-18		2.00	5.40	35.92		4.89		120.4	17			222.						
-20		[illegible]	3.62	15.85		4.42	9.13	151.8				290.						
-21		[illegible]	3.27	15.16		[illegible]	8.14		10	10.00		129.						
-26		1.00	4.60	22.45		5.00	9.97	140.1		[illegible].00		[illegible]						
-14		1.33	8.03	[illegible]	6	3.67	14.45	305.1		9.00		[illegible]						
-1[illegible]						4.15						91						
-22		1.83	2.77	9.51	14	4.29	4.08	29.3			7.18	1[illegible]						
-25		1.00	2.00				3.30	51.40		9.11	1[illegible]	151.						
-35	*	[illegible]	5.78	39.31		4.11	10.62	167.0					1					
-36	1	1.00	4.50	20.25		[illegible]	4.38		17	10.06								
-37	1	1.50	4.08	25.37	1	5.25					14.33	136.						
-38		1.67	[illegible]	27.51	1	[illegible]	6.05	58.07				1[illegible]						
-39	1	2.00	4.65	27.65		5.25				9.07								

One penalty for using constrained regressions is that there is no widely accepte simple quantity that reflects the degree of agreement between the equation and the dat in the way that the "coefficient of determination," called r^2, does for unconstrained regressions. If y_i represents a bulk depth data point to be fitted by regression, $\hat{y}_i$ the value of the bulk depth predicted by the regression expression, and $\bar{y}$ the average of the data points to be fitted, then, by statistical theory the expression for the coefficient of determination for a constrained regression should be

$$r^2 = 1 - \Sigma(y_i - \hat{y}_i)^2/\Sigma(y_i^{\,2}).$$

This quantity is, however, a poor measure of the "goodness" of the regression equatio So we have used, in this presentation, a nonrigorous but intuitively more appealing measure of the suitability of the regression description:

$$s = 1 - \Sigma(y_i - y_i)^2/\Sigma(y_i - \bar{y})^2.$$

This parameter compares the variance about the regression to the variance about the m as does "r^2" for an unconstrained regression, but it is not limited numerically to th range 0 to 1. It is restricted only to be less than unity, and can be negative.

RESULTS AND DISCUSSION

Depth Versus Intercept Counts

Regression results for all of the skidding, species, and age combinations obtaine in the study are shown in table 3. The relationships for skyline and helicopter skidding were similar; so they were combined and called "high-lead." The high values of the fit descriptor, s, are largely due to the manner of aggregating data. Examples of fit are shown in figures 1, 2, and 3. Because of the data aggregation, tests for differences among the slash groups seem irrelevant. However, recognizing the large amount of variation among sampling points and the similarity of some of the regression in table 3, the equations in figure 4 are recommended for application to fire modeling To obtain the equations for initial depth shown in figure 4, some of the results in table 3 had to be adjusted to age 1 year.

Merchantable top diameter limits and d.b.h. of trees thinned precommercially appear to significantly influence the depth-intercept count relationship. We were unable to include a wide range of conditions for these factors; thus, application of our results should be restricted to conditions similar to ours. Applicable conditions include merchantable top diameters of 4 to 6 inches for pine and 5 to 6 inches for oth species, and precommercial thinning of trees 2 inches and greater in d.b.h.

TABLE 3.--*Constrained regression through aggregated data points* [illegible] *of intercepts of 1/4- to 1-inch particles in* [illegible]

Type of cutting	Dominant species	Age of debris (year)	Sample included for [illegible]: Year	Units	Regression results: [illegible]	[illegible]	Figure [illegible]
Ground-lead harvest, 6-in top	DF, mix	1	1975	2, 11, 13, 14	[illegible]	0.86	
Ground-lead harvest, 6-in top (slashed after harvest removed)	DF	[illegible]	1975	[illegible]	[illegible]	.87	
Ground-lead harvest, 6-in top (slashed after harvest removed)	DF	1	1975	10, 12	[illegible]	.86	
Ground-lead harvest, 6-in top	DF	[illegible]	1975	3, 5	[illegible]	.71	
Ground-lead harvest, 5-in top	LP	1, 3	1975 1976	23, 24, 25, 26; [illegible]	[illegible]	.88	
Ground-lead harvest, 6-in top	DF, mix	1,2,3	1975	2,3,5,7,8,9,10,11,12,13,14	$y = 3.27\sqrt{x}$	[illegible]	[illegible]
Ground-lead harvest, 5-in top	LP	1	1976	23, 24, 30	[illegible]	[illegible]	
Precommercial thinning	PP	4	1976	10, 12, 13, 15, 16	[illegible]	.92	
Precommercial thinning[1]	LP	4	1976	1, 5, 6, 17	[illegible]	.98	
Precommercial thinning	DF	[illegible], 4	1975	4, 15, 16, 17, 18, 19, 22	$y = 4.75\sqrt{x}$	.90	[illegible]
Precommercial thinning	LP, PP	1	1976	9, 27, 28, 29, 31	$y = 5.58\sqrt{x}$	.94	
High-lead harvest, 6-in top	Mix	1	1976	18,20,21,26,35,36,37,38,39	[illegible]	.91	[illegible]
High-lead harvest, 6-in top (lopped by harvest crew)	Mix	1	1976	14, 19, 22, 25	[illegible]	.96	

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[1] These units are not typical of current practice, as trees of large d.b.h. were thinned. The relationship developed was not used for model purposes for this reason.

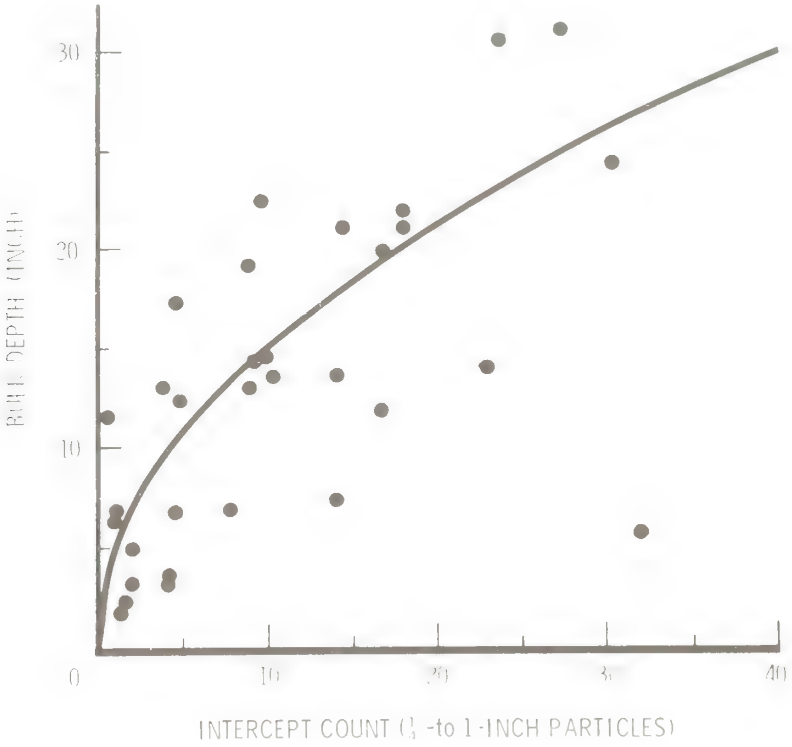


Figure 1.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for precommercial thinning. Analysis is shown in table 3.

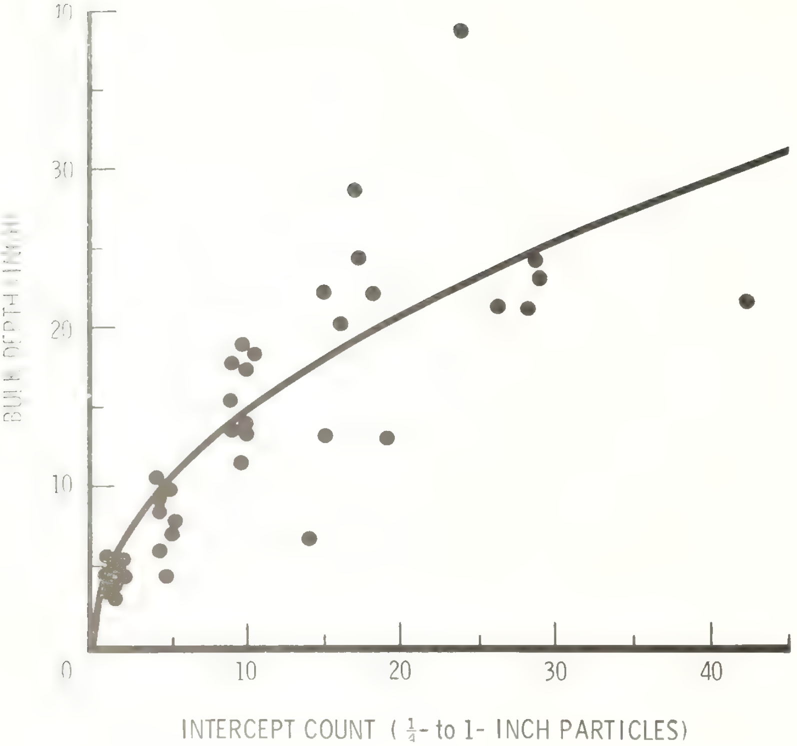


Figure 2.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particle per 4 feet of transect) for high-lead skidding. Analysis is shown in table 3.

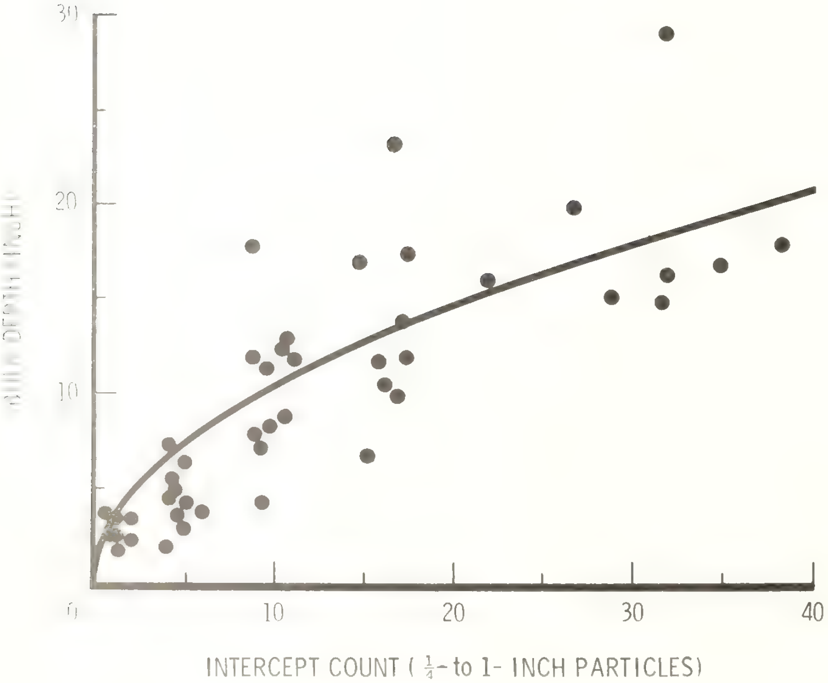
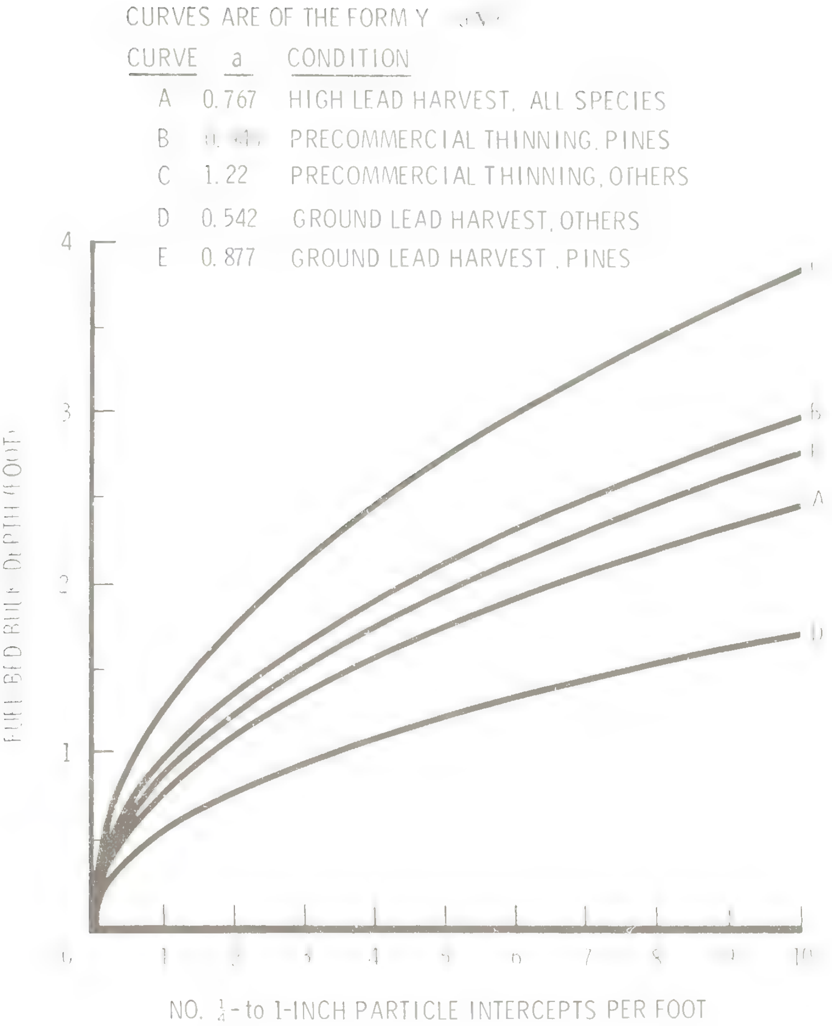


Figure 3.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for ground-lead skidding. Analysis is shown in table 3.



[illegible] between fuel bed bulk depth (first year) and expected number of intercepts per foot of transect for modeling fire behavior in slash.

Bulk Depth Versus High Intercept Depth

Measurement of bulk depth is time consuming and subject to personal interpretation. However, the simpler to measure "high intercept depth" (Brown 1974) tends to underestimate fuel bed compactness, resulting in a systematic overestimation of the rate of fire spread and reaction intensity by Rothermel's (1972) model (Brown 1972; Bevins 1976; Hough and Albini 1978). But because it is rapid, reliable, and widely used, we determined the regression relationship between high intercept depth and bulk depth to provide a formula that can be used to reduce the high intercept measurements for use in the Rothermel fire spread model. The analysis was made on pairs of bulk depth and high intercept depth measurements taken at each point.

Examination of a large number of regressions for various combinations of skidding, species, and age revealed no substantive differences between the regression coefficients.

Also, all the regression lines passed very nearly through the origin. For example, treating all debris of age 2 years and less as one set and all debris older than 2 years as another set gave the following relationships:

$$\text{AGE} \leq 2:\ y = -0.0245 + 0.661X \qquad (r^2 = 0.78)$$
$$\text{AGE} > 2:\ y = 0.303 + 0.602X \qquad (r^2 = 0.74)$$

where

y = bulk depth (inches)
x = high intercept depth (inches).

Variation among regression coefficients was restricted as shown by the histogram of ratios of bulk depth-to-high intercept depth computed for 118 transects (fig. 5). Sixty percent of the ratios were between 0.55 and 0.75. Regression coefficients pertaining to the major skidding, species, and age groups are shown in table 4. Variability of coefficients within slash groups is comparable to variability among slash groups. Thus, the narrow range of variability and probable difficulty in establishing significant differences among slash groups seems to warrant application of one relationship between bulk depth and high intercept depth to all slash. Combining all measurements produced the regression:

$$y = 0.638X$$
$$(s = 0.76)$$

which simply states that bulk depth is 64 percent of high intercept depth. This compares with 52 percent observed by Bevins (1976) in studying Douglas-fir and hemlock slash in Washington.

Interestingly, the finding of 64 percent is consistent with fire spread verification studies (Brown 1972; Bevins 1976; Hough and Albini 1978) in which fuel bed depths that were reduced by factors in the range of 0.6 to 0.7 improved fire spread predictions by the Rothermel model.

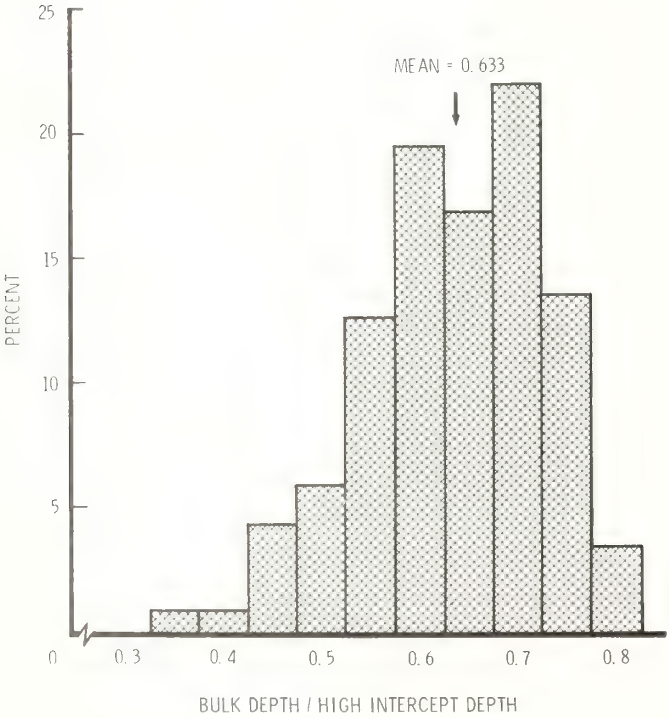


Figure 5.--Histogram of regression coefficients for the constrained relationship between bulk depth versus high intercept depth determined for individual transects.

TABLE 4.--*Constrained-regression coefficients (b = ratio of bulk depth to high-intercept depth) for skidding, species, and age groups*

Type of cutting	Dominant species	Age of debris (years)	Areas included	b-coefficient	
				Average	Standard deviation
Ground-lead harvest	DF	0-1	1975-2,10,11,12,13,14,20	0.610	0.030
Ground-lead harvest	DF	3-4	1975-3,5,7,8,9	.599	.031
Ground-lead harvest	LP	3	1975-23,24,25,26	.596	.079
Ground-lead harvest	LP	1	1976-3,4,23,24,30	.698	.036
Precommercial thinning	PP	4	1976-10,12,13,15,16	.592	.107
Precommercial thinning	LP	3-4	1976-1,2,5,6,7,17	.653	.066
Precommercial thinning	DF	3-4	1975-4,15,16,17,18,19,21,22	.575	.092
Precommercial thinning	PP	1	1976-9,11,27,28	.713	.059
Precommercial thinning	LP	1	1976-29,31	.689	.086
Skyline harvest	Mixed	1	1976-14,18,19,20,21,22,25,26	.673	.036
Helicopter harvest	Mixed	1	1976-35,36,37,38	.631	.048

Effect of Lopping

The effect of lopping was evaluated by combining bulk depths determined before and after lopping, as a data pair for each study area and computing a linear regression constrained through the origin. The resulting equation is plotted over the scatter diagram shown in figure 6. Similarly, the data from all precommercial thinning areas were combined for regression (as shown in fig. 7). The quality of the relationships expressed by "s" values of 0.91 and 0.69, respectively, was good. Note that the ratio of the regression coefficients in table 3 for lopped and unlopped high-lead harvest debris (3.60/4.60 = 0.78) is quite close to our result of 0.83 (fig. 6).

HAZARD Model Application

To illustrate how this study has been utilized, sample printouts of fuel inputs (fig. 8) and fire behavior predictions (fig. 9) are shown for the slash HAZARD model now in use by USDA Forest Service Northern Region. This model affords managers the opportunity to assess the fire implications of tree cutting activities before debris is put on the ground. The fuel loadings required to run the HAZARD model are generated from tree inventories processed through a debris prediction model.[5] The debris prediction model provides total potential debris for all trees on a site. Managers then tailor the total potential debris to specific cutting prescriptions and submit the data for processing by the HAZARD model. To ease checking of the transferred data, the HAZARD model prints out the input data (fig. 8).

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[5] See footnote 4.

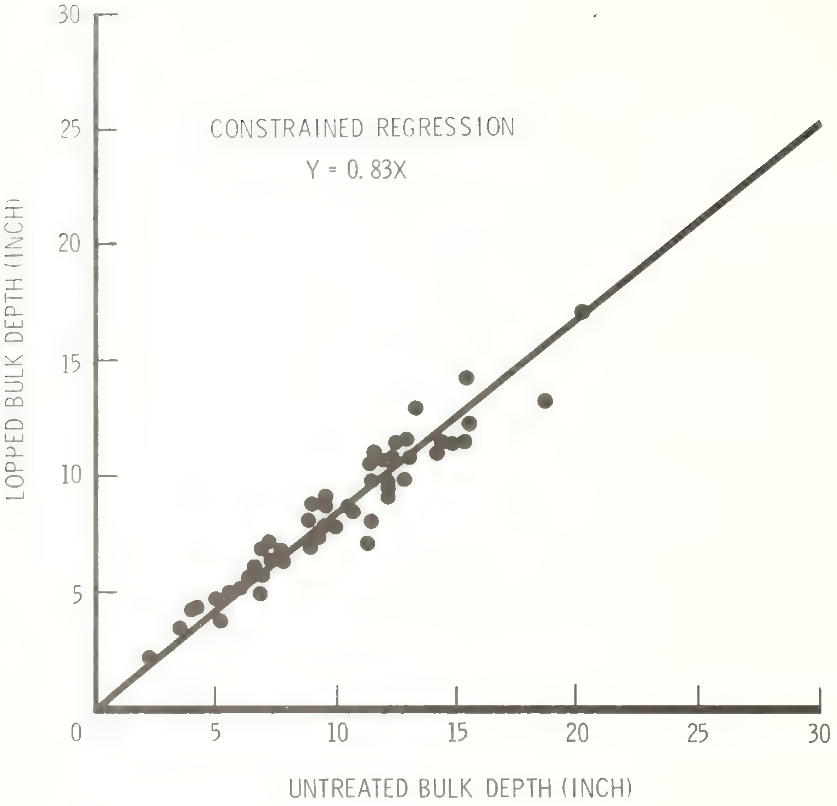


Figure 6.--Bulk depth of lopped slash as a function of bulk depth of unlopped slash for all timber harvest conditions

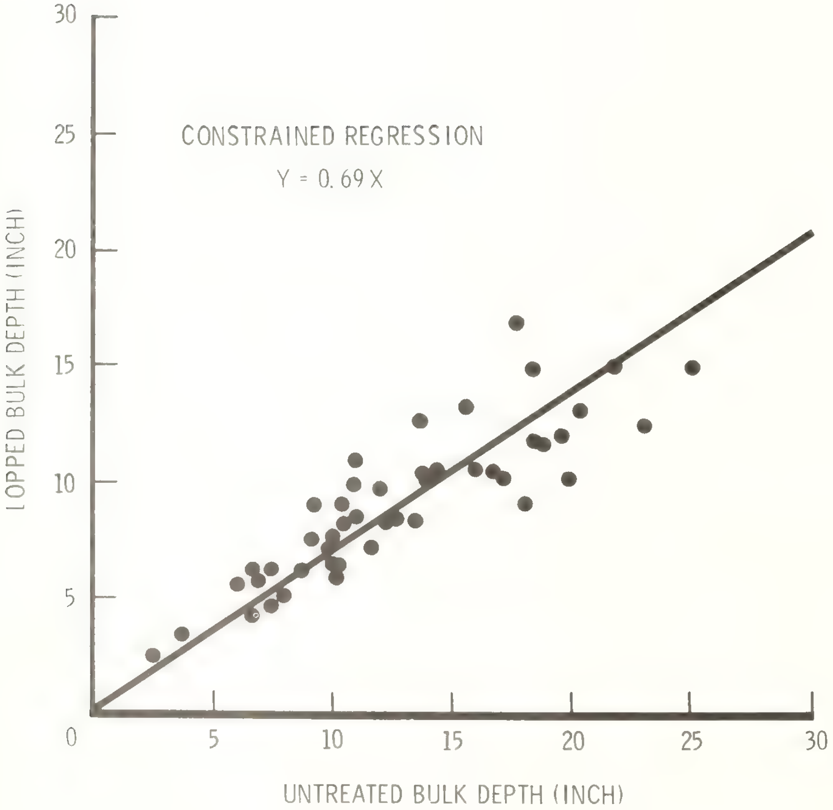


Figure 7.--Bulk depth of lopped slash as a functio of bulk depth of unlopped slash for precommercial thinning.

```
          ACTIVITY FUEL FIRE HAZARD ASSESSMENT                          INPUT SUBMITTED BY..........

                                                                        OUTPUT CHECKED BY..........

              EXAMPLE INPUT/OUTPUT FOR HAZARD PROGRAM                            DATE..........

DEBRIS-PREDICTION INPUT DATA ...
      SPE-                                 LOADING (T/A)  BY  DBH  CLASS
SIZE  CIES  0-1    1-2    2-3    3-4    4-5    5-6    6-7    7-8    8-9    9-11  11-13  13-15  15-17  17-19  19-25  25-30   30+

-3IN  GF     .39   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   2.40   3.00   3.20    .99   1.90   1.00   0.00   0.00
3+IN  GF    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00    .88    .31    .47    .11    .15    .08   0.00   0.00
FULL  GF    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   1.70   2.50   3.10   1.00   3.60   5.10   0.00   0.00
-3IN  WL    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   1.70   0.00    .72   0.00   0.00   0.00   0.00
3+IN  WL    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00    .70   0.00    .17   0.00   0.00   0.00   0.00
FULL  WL    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   1.90   0.00    .37   0.00   0.00   0.00   0.00
-3IN  ES     .04   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00    .37   0.00   0.00   0.00   0.00
3+IN  ES    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00    .10   0.00   0.00   0.00   0.00
FULL  BKG   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   2.10   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00

      ACTIVITY-PRODUCED FUELS ... 3 IN AND LESS =   15.9 ... OVER 3 IN =   31.5 ... TOTAL =  47.4

                                           NUMBER OF WINTERS
      AVG FUEL DEPTH, FT          1      2      3      4      5
           ORIGINAL CONDITION   1.12   1.12   1.12    .96    .91
           LOPPED TO 2-FT STD    .94    .94    .94    .82    .69

DOWN-WOODY INVENTORY ...              LOADING IN TONS/ACRE
                              1 HR  10HR  100H   3-5    6-9   1020   20 +
           DOWN SOUND           .5   1.0   1.5   3.0    5.0    5.0    2.5      3 IN AND LESS =   3.0 ...  TOTAL =  18.5
           DOWN ROTTEN                           0.0    0.0    0.0    0.0                          ...  TOTAL =   0.0

OTHER INPUT DATA ...
      NOMINAL GRASS LOADING =   0.0      MEASURED DUFF LOADING =  10.0      AVERAGE SLOPE (PERCENT) =  40

      ACTIVITY ... GROUND-LEAD TIMBER HARVEST              UTILIZATION STANDARD = 5.0 INCH TOP            RUN  1, NOV 77
```

[illegible]

```
EXAMPLE INPUT/OUTPUT FOR HAZARD PROGRAM
                 ORIGINAL CONDITION
POTENTIAL FIRE BEHAVIOR FOR SEVERELY-DRY CONDITIONS-
(ONE-HOUR TIMELAG FUEL MOISTURE CONTENT = 5 PERCENT)


  QUANTITY     20-FT.    SLASH AGE IN NUMBER OF WINTERS
  ASSESSED      WIND          1              3            5
                MI/H        -----          -----        -----
............     0            4              3            1
 HEAD FIRE       5            7              5            3
SPREAD RATE     10           12              8            4
CHAINS/HOUR     15           19             13            6
............    20           27             18            8

............     0           15             11            6
 PERIMETER       5           24             17           10
GROWTH RATE     10           36             24           13
CHAINS/HOUR     15           47             31           16
............    20           57             37           17

............     0            2              1            0
BURNED AREA      5            5              2            1
AFTER 1 HOUR    10           11              5            1
BURN, ACRES     15           20              9            2
............    20           29             12            3

............     0            6              5            3
 HEAD FIRE       5            9              7            5
FLAME LENGTH    10           11              8            6
  IN FEET       15           14             10            7
............    20           16             12            8

............     0           47             31           19
CROWN SCORCH     5           65             41           22
HEIGHT IN FT    10           76             43           18
BY HEAD FIRE    15           82             42           16
............    20           86             42           14

............     0          324            176           81
INTENSITY AT     5          600            335          158
HEAD OF FIRE    10         1081            584          254
(BTU/SEC/FT)    15         1688            885          358
............    20         2395           1224          468

RESIDUAL FIRE FROM BURNOUT OF LARGER FUELS (AND DUFF)

HEAT LOAD (BTU/SQFT)   16439          15202        14344
BURN TIME (MINUTES)      69             69           69

GRD. LEAD HARVEST  UTL. STD.  6.0 IN    RUN  14 NOV 77
```

Figure 9.--Sample printout of fire behavior predictions by HAZARD program, based on fuel inputs shown in figure 8.

Fire behavior predictions are furnished in the [illegible] debris (as shown in fig. 9). A further discussion of model output and a guide to interpretation of the fire behavior numbers are in the Northern Region's Users' Guide.[6]

Fuel Bed Depth Prediction

To predict fuel bed depth, predictions of slash in tons per acre are converted to number of 1/4- to 1-inch intercepts through two manipulations. First, weight per unit area is converted to number of 1/4- to 1-inch intercepts by species, using a constant multiplier that is inversely proportional to the product of wood density of the 1/4- to 1-inch pieces and their mean square diameter (Brown 1974). Table 5 gives the conversion factors for 11 western conifer species.

Table 5.--*Factors for converting from 1/4- to 1-inch size class fuel loading to "expected number of intercepts per foot of random transect perpendicular to the ground" for 1/4- to 1-inch size class limb wood of different species*

Species of tree	Factor for tons/acre	Factor for lb/ft[illegible]
Ponderosa pine	0.4309	[illegible]
Lodgepole pine	.5871	12.79
Western larch	.4382	9.55
Douglas-fir	[illegible]	[illegible]
Grand fir	.7295	[illegible]
Subalpine fir	.5784	[illegible]
Western redcedar	.6400	[illegible]
Western white pine	.5258	[illegible]
Western hemlock	.5950	12.96
Engelmann spruce	[illegible]	[illegible]
Whitebark pine	.5258	[illegible]

Next, number of intercepts are combined for different species. Equations have been given that relate bulk depth to the count of 1/4- to 1-inch fuel intercepts in two crossed, 2-foot vertical planes (this relationship is the same as that for a randomly placed single 4-foot vertical plane). The equations for the pines and for other conifers are different, so in some cases a method of combining them is necessary.

The depth prediction equation can be written for slash of one species type as:

[illegible]

where

[illegible] = initial bulk depth

x = expected number of intercepts of 1/4- [illegible] placed 1-foot vertical plane.

---

[6] See footnote 3.

The quantity x is proportional to the average loading on the site of 1/4- to 1-inch fue pieces. When only pines are present in the fuel bed, or when none are present, this formula provides a prediction of fuel bed depth for fire modeling. But when both types are present, the mixed species fuel bed depth will contain contributions for both types The model for mixed type fuel bed depths used in the HAZARD model is as follows:

Let x_1 = expected 1/4- to 1-intercept count per foot for pine types,

and x_2 = expected 1/4- to 1-intercept count per foot for other types.

If the two types are randomly distributed over the site, then the fraction of the total 1/4- to 1-inch size class loading that is pine type should be (ignoring particle densit differences) f_1, where

$$f_1 = x_1/(x_1 + x_2)$$

and the fraction for other types is f_2, where

$$f_2 = x_2/(x_1 + x_2) = 1 - f_1.$$

Now, if the two types were segregated on the site, so that a fraction f_1 of the site area would be covered by pine species and f_2 by others, the expected intercept count *in* the pine-covered area would be x_1/f_1 and the bulk depth in the pine-covered area would be

$$\delta_o^{(1)} = a\sqrt{x_1/f_1}.$$

Similarly, the bulk depth of the other fraction of the area would be

$$\delta_o^{(2)} = a_2\sqrt{x_2/f_2}.$$

On such a segregated site, the *average* bulk depth would be $\overline{\delta}_o$, where

$$\overline{\delta}_o = f_1\delta_o^{(1)} + f_2\delta_o^{(2)}.$$

We take this latter expression to be the average fuel bed depth for the mixed type situation. This equation can be rewritten by substituting for the f and δ_o values to give

$$\overline{\delta}_o = (a_1x_1 + a_2x_2)/\sqrt{x_1 + x_2}.$$

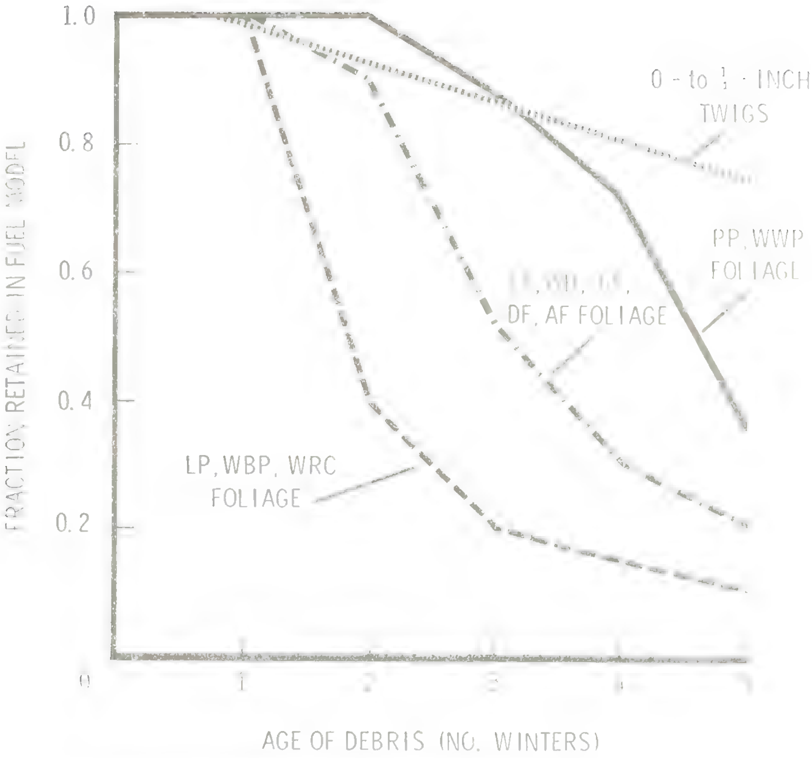
Other factors that affect initial fuel bed depth are reflected in this formula by chang ing the values of a_1 and a_2 in accordance with the results discussed earlier (fig. 4).

Foliage Loss and Settling

The early effects of aging on debris fuels are settling of the fuel bed and loss foliage and fine twigs to the forest floor. For modeling fire behavior in slash, it i necessary to quantify rate of settling and the loss of foliage and fine twigs. To operate the HAZARD model, data from Olson and Fahnestock (1955), Fahnestock and Dieteri (1962), Steele (1960), Wagener and Offord (1972), and Brown (1970a) were integrated to describe loss of material (fig. 10). Not all foliage that drops from the branches was excluded from the fuel complex because some foliage remaining in the litter layer and suspended as mats in the slash is still available as fuel for a surface fire.

Settling of slash was modeled as a reduction in depth using table 3, Fahnestock and Dieterich (1962), and Kiil (1968). This study, together with others cited, permitt construction of a settling model adequate for hazard appraisal (fig. 11).

Figure 10.--Reduction of quantity of foliage and small twigs for modeling fire behavior in slash. Not all foliage detached from limbs is lost from fuel available to spread fire.



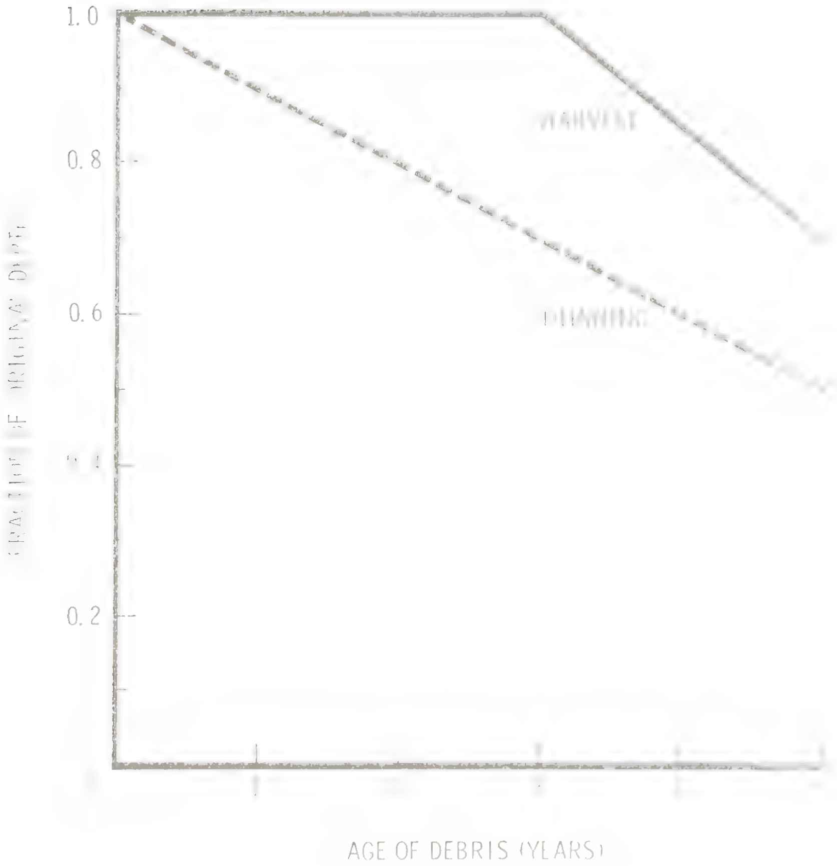


Figure 11.--Settling of slash expressed as a function of the original depth over time for harvesting and precommercial thinning slash.

SUMMARY

To aid in modeling fire behavior for appraisal of slash hazard, equations were leveloped for predicting fuel bed depth from the loading of 1/4- to 1-inch fuels. The lepth equations differed among precommercial thinning, ground-lead harvesting, and iigh-lead harvesting systems and between pines and other conifers. Settling of slash vith age was weakly discerned; however, our findings, together with others, permitted inference of a rough aging model that distinguishes between harvesting and precommercial thinning.

Depth of lopped slash was strongly related to depth of unlopped slash. A strong relationship was also developed between the "bulk depth," useful in fire behavior modeling, and the "high intercept" depth that is easily measured in the field. The influence of merchantable tip diameter on slash depth was evident, although it was not quantified. Accuracy of the depth relationships is probably adequate for most tree cutting activities in western mountainous areas, except perhaps west side slopes along the Pacific Coast. Here the large trees and methods of logging may result in depth/load relationships different from ours. Depth predictions should be verified in the Pacific Coast mountains before modeling fire behavior in slash.

When predictions of fuel depth are coupled with predictions of slash loading (by size class) from tree inventories, the depth models presented here allow prediction of fire behavior before the slash is created. Hopefully, this information will aid in timber sale planning and in management of slash fuels.

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KEYWORDS: slash, fire behavior modeling, fuel compactness.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

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FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

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MATHEMATICAL ANALYSIS OF FOREST FIRE SUPPRESSION

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RESEARCH SUMMARY

This paper presents a mathematical formulation of the construction of a containment perimeter for a wildland fire. The formulation permits the calculation of total burned area, final perimeter, and containment time, if the rate of growth of the fire can be specified as a function of time and position. Using a simple but flexible fire shape function, numerical results are given, showing the influence of the rate of spread in the front, flank, and back directions expressed in ratio to the rate of control line construction. These results may be useful in presuppression planning and effectiveness analyses. This paper is the result of collaborative effort carried out as part of the U. S. /U. S. S. R. scientific-technical exchange program in forestry.

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PREFACE

In October 1976, as part of a technical-scientific exchange program in forestry, a team of forest fire specialists from the United States visited the Soviet Union. Frank Albini, representing Forest Fire and Atmospheric Sciences Research, worked at the Leningrad Forestry Research Institute. The Institute is the main organization performing fire research for protecting forests in the Soviet Union.

Dr. Albini collaborated with Candidate Georghy N. Korovin, chief of the computational methods laboratory, and members of his staff, including Ms. E. H. Gorovaya, on the analysis presented in this paper. The group formulated the scope of the analysis, methods of computation, and mathematical expressions. Numerical results were generated independently and compared later. This paper, in Russian, is included in the annals of the Leningrad Institute for 1977. The translation presented here should be useful in tactical planning for forest fire suppression, a matter of practical importance in both countries.

INTRODUCTION

In the process of planning and [illegible] it is often desirable to have available [illegible] in fire suppression and the results to be [illegible]. It is the purpose of this paper to introduce a mathematical method for the analysis of fire suppression (or fire containment) activity which can be used to derive such relationships. We show, by example, how the method can be applied to determine the burned area and the time required for suppression, using a simple but flexible expression for the shape of the fire.

In addition, we explore the sensitivity of the burned area and the time required for suppression to the following factors:

(1) The size of the fire at the start of suppression.

(2) The rate of spread of the fire in the front, flank, and back directions, and a parameter describing the shape of the fire.

(3) The rate of suppression (or rate of control line construction).

(4) The tactics employed.

In the following section we introduce the basic concepts of and the limitations on the method of analysis and present the general analytical forms. In subsequent sections we introduce simplifying assumptions, present examples, and extend the analysis to the situations requiring a change of tactics to stop a rapidly spreading head fire.

BASIC CONCEPTS AND LIMITATIONS OF METHODS

We seek to describe analytically the rate [illegible] suppression force as a function [illegible] purpose, we assume that the work proceeds, if possible, at the edge of the fire. It is not important whether the effort [illegible] suppression in U.S. fire control terminology), or toward construction of a barrier across which the fire will not spread. [illegible] containment is the same. But it is necessary to restrict our attention to fires which do not spread by spotting and [illegible]

If the fire meets the conditions [illegible] ment) proceeds at the fire edge, it is possible to determine the boundary of burned area and the time that the work will require, if [illegible] expressed analytically as a function of position and time.

Employing polar coordinates, let r(θ, t) be the distance from the point of ignitio to the edge of the fire at time t and in the direction given by the angle θ (measured from an arbitrary fixed direction). Here we insist that r(θ, t) be single valued, possess a positive time derivative, and be differentiable with respect to θ. If the rate of progress of a fire-suppression crew, working at the edge of the fire, can be expressed as λ(θ, t), then we can write the equations for the generation of the final boundary, R(θ).

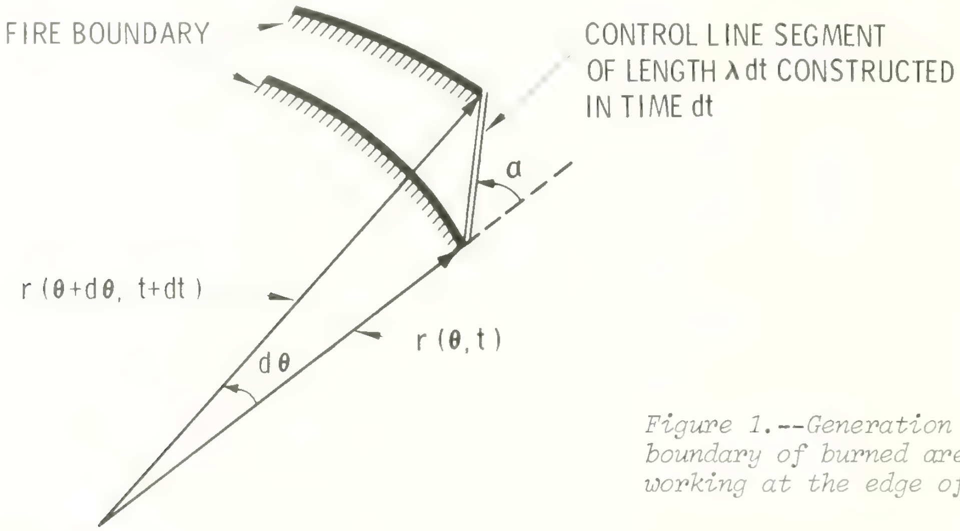


Figure 1.--Generation of final boundary of burned area by crew working at the edge of a fire.

Referring to figure 1, assume a differential element dt of time to elapse. During this time the crew will construct an element λdt of the final boundary. In order to remain in contact with the advancing edge of the fire, this element of the boundary curve must be constructed at an angle α (measured counterclockwise) with respect to the direction θ. We can write the formulae for the components of the arc λdt in the tangential and radial directions from inspection:

$$d\theta = (\lambda dt) \sin \alpha / r(\theta, t) \qquad (1)$$

$$dR = (\lambda dt) \cos \alpha = r(\theta + d\theta, t + dt) - r(\theta, t) = \frac{\partial r}{\partial \theta} d\theta + \frac{\partial r}{\partial t} dt \qquad (2)$$

Substituting dθ in equation 2 from equation 1, and employing the short notation

$$\frac{\partial r}{\partial \theta} = r' \; ; \; \frac{\partial r}{\partial t} = \dot{r}$$

we find

$$\lambda \cos \alpha = (r'/r) \lambda \sin \alpha + \dot{r} \qquad (3)$$

Squaring both sides of equation 3 and solving for sin α we obtain

$$\sin \alpha = \frac{-(\dot{r}/\lambda)\ (r'/r) + \sqrt{1 + (r'/r)^2 - (\dot{r}/\lambda)^2}}{1 + (r'/r)^2} \qquad (4)$$

$$\cos \alpha = \frac{(\dot{r}/\lambda) + (r'/r)\sqrt{1 + (r'/r)^2 - (\dot{r}/\lambda)^2}}{1 + (r'/r)^2} \qquad (5)$$

Equations 1 and 2 can be [illegible] the burned area, R (θ):

[illegible]

[illegible]

The last four [illegible] tion the limitations mentioned above.

[illegible]

[illegible]

The right hand [illegible] in the [illegible] obvious [illegible] ing the fire.

SIMPLIFYING ASSUMPTIONS

To gain further insight into the relative importance of the various factors outlined above, we introduce simplifying assumptions which permit closed form solutions of equations 6 and 7 and make possible numerical examples.

First, we assume that the shape of the [illegible] ally and that the form of the fire is invariable. [illegible] simply expands linearly with time, and, [illegible] tains its shape. This assumption [illegible] ing in continuous, homogeneous fuel on flat terrain or gentle slopes, and that the wind does not change speed or direction. Such idealized conditions never occur exactly, but many fires approximately satisfy these conditions at least for short periods of time.

Since we assume that the fire boundary grows linearly with time, the shape of the fire, expressed in polar coordinates, is the same as the distribution of radial rates of spread as a function of the polar angle. We establish the reference direction ($\theta = 0$) to be in the direction of the maximum rate of spread, and express the radial rate of spread as:

$$\dot{r}(\theta) = \begin{cases} V_f + (V_F - V_f)\cos^n\theta, & 0 \le \theta \le \pi/2 \\ V_B + (V_f - V_B)\sin^n\theta, & \pi/2 \le \theta \le \pi \end{cases} \qquad (9$$

where: V_F = the forward or frontal rate of spread

V_f = the rate of spread at the flank

V_B = the backing rate of spread

n = a shape parameter to be determined empirically for various fuel types.

This functional form is quite flexible, and can be used to generate a wide variety of shapes. Figure 2 displays some of the shapes generated by this formula; in the figure all shapes are normalized by the maximum dimension (that is, $\dot{r}(\theta)/V_F$ is plotted)

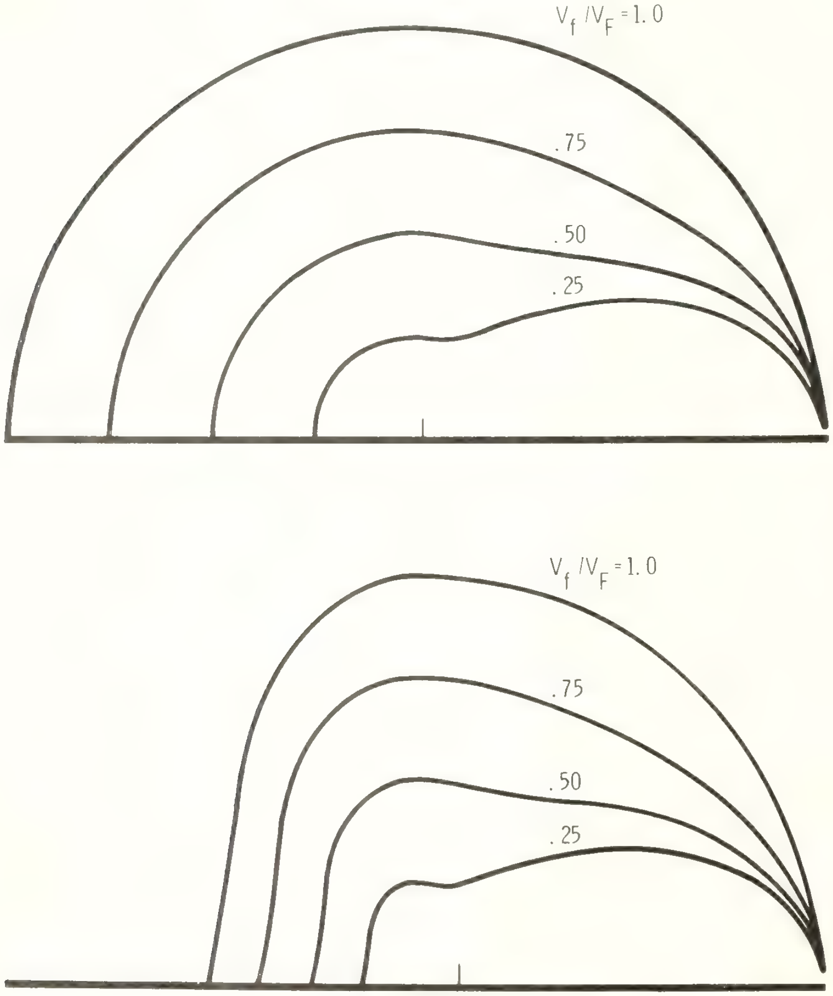


Figure 2.--Shapes of fires generated by equation 9. In all cases, the fire perimeter is drawn to a scale such that the distance from the point of ignition (tic mark on horizontal line) to the head of the fire (right hand edge of each outline) is the same. In the upper figure $V_F/V_f = 1.0$; in the lower figure $V_F/V_f = 0.5$; for both figures $n = 4$.

Table 1.--Area and perimeter of free-burning fires for different values of fire shape parameters

$\frac{V_f}{V_F}$	$\frac{V_B}{V_f}$	n = 1		n = 2		n = 4	
		Area	Perim	Area	Perim	Area	Perim
		$r^2(o)$	$r(o)$	$r^2(o)$	$r(o)$	$r^2(o)$	$r(o)$
0.1	0.25	0.841	3.33	0.641	[illegible]	[illegible]	2.64
	.50	.843	3.32	.644	[illegible]	[illegible]	[illegible]
	.75	.845	3.33	.646	[illegible]	.481	[illegible]
	1.0	.848	3.35	.650	[illegible]	.485	2.71
0.2	.25	.922	3.53	.720	3.11	[illegible]	2.84
	.50	.929	3.51	.728	[illegible]	[illegible]	2.86
	.75	.938	3.53	.740	3.16	[illegible]	2.91
	1.0	.948	3.58	.754	[illegible]	[illegible]	3.00
0.3	.25	1.03	3.76	.825	[illegible]	.650	3.08
	.50	1.04	3.73	.844	[illegible]	.671	3.11
	.75	1.06	3.76	.869	3.41	[illegible]	3.18
	1.0	1.09	3.83	.901	[illegible]	.741	3.31
0.4	.25	1.16	4.01	.956	3.60	[illegible]	[illegible]
	.50	1.19	3.97	.990	3.61	.816	[illegible]
	.75	1.22	4.01	1.03	3.69	.870	[illegible]
	1.0	1.26	4.10	1.09	[illegible]	[illegible]	3.65
0.5	.25	1.32	4.28	1.11	[illegible]	[illegible]	3.64
	.50	1.36	4.24	1.17	[illegible]	[illegible]	3.68
	.75	1.42	4.28	1.24	4.01	1.08	3.81
	1.0	1.48	4.40	1.32	4.18	[illegible]	4.03
0.6	.25	1.50	4.59	1.30	4.21	1.12	3.96
	.50	1.56	4.54	1.37	[illegible]	1.20	4.01
	.75	1.64	4.59	1.47	[illegible]	[illegible]	4.17
	1.0	1.74	4.73	1.60	4.55	1.48	4.43
0.7	.25	1.71	4.92	1.51	4.56	[illegible]	[illegible]
	.50	1.79	4.86	1.61	[illegible]	1.44	[illegible]
	.75	1.90	4.92	1.75	4.72	1.61	4.56
	1.0	2.03	5.08	1.92	[illegible]	1.82	4.85
0.8	.25	1.94	5.28	1.74	4.93	[illegible]	4.68
	.50	2.05	5.21	1.88	[illegible]	[illegible]	4.76
	.75	[illegible]	5.28	2.06	[illegible]	[illegible]	[illegible]
	1.0	2.36	5.46	[illegible]	[illegible]	2.22	[illegible]
0.9	.25	2.20	[illegible]	2.01	[illegible]	1.84	5.08
	.50	2.34	5.58	2.17	[illegible]	[illegible]	5.16
	.75	2.52	5.66	2.40	[illegible]	2.30	5.40
	1.0	2.73	[illegible]	2.69	[illegible]	2.65	[illegible]
1.0	.25	[illegible]	6.05	2.29	[illegible]	[illegible]	[illegible]
	.50	[illegible]	5.97	2.50	[illegible]	2.36	[illegible]
	.75	2.88	6.05	2.79	[illegible]	2.70	[illegible]
	1.0	3.14	6.28	[illegible]	6.28	[illegible]	6.28

Throughout the rest of this paper we will employ dimensionless forms for all parameters and results. Table 1 gives values for the perimeter length and the area of various fire shapes generated using equation 9. In this table the perimeter length is normalized by r(0) and the area by $r^2(0)$, where r(0) is the distance from the point of origin to the head (or front) of the fire. These values may be used to compare sensitivities in absolute terms, because later results will be given in terms of the initial fire perimeter length and initial fire area.

The second simplifying assumption we make is that the fire is to be suppressed (or contained) through the work of two crews which divide the effort equally. This assumption not only introduces the simplification of mathematical symmetry, but reflects current practice both in the United States and the Soviet Union. The advantage of this tactic is clear upon a little thought: If the work of suppression proceeds in only one direction from the starting point, then when the crew completes its circuit around the fire edge, it will encounter the fire burning behind the original line of control near the starting point. If the work proceeds in both directions from the starting point, then when the two teams meet on the opposite edge of the fire the containment will be complete.

The third assumption employed here is that the rate of progress by the suppression crew (λ) is constant. This is a good approximation for machine-aided effort, but is clearly not a good approximation for work with handtools or backpack pumps (with the possible exception of the new Soviet technique of backfiring against a line of foam laid down using a backpack cannister). It would be a little more complex to assume that the rate of suppression is a simple function of the rate of advance of the fire edge perpendicular to the boundary (see inequality 8) which quantity is proportional to the fire intensity as defined by Byram (1959). For instance, one might argue that direct suppression will progress at a rate inversely proportional to the depth of the flaming zone. This depth is, in turn, approximately proportional to the rate of advance of the fire edge (Albini 1976). For the purpose of exploring the sensitivity of burned area and time required for containment to various factors, however, it is sufficient to use a constant work rate.

Using these simplifying assumptions it is possible to write closed form expressions for the burned area and the time expended. Dividing equation 7 by equation 6 and integrating we obtain the formula for the shape of the final boundary:

$$R(\theta) = R(\theta_o)\ \exp\left(\int_{\theta_o}^{\theta} f(\theta')\,d\theta'\right) \tag{10}$$

In this equation the function to be integrated is

$$f(\theta) = \frac{\dot{r}/\lambda + (r'/r)\sqrt{1 + (r'/r)^2 - (\dot{r}/\lambda)^2}}{-(r'/r)(\dot{r}/\lambda) + \sqrt{1 + (r'/r)^2 - (\dot{r}/\lambda)^2}} \tag{11}$$

which is, under our assumptions, purely a function of the angle θ, since $\dot{r}$ (θ) is given by equation 9 and

$$r'/r = \left(\frac{d}{d\theta}\dot{r}(\theta)\right)/\dot{r}(\theta) \tag{12}$$

Note that the value of R(θ) depends upon the choice of the starting point, θ_o. If the effort begins at the front edge of the fire on the line of symmetry, then

$$\theta_o = 0;\ R(\theta_o) = r_o(0) \tag{13}$$

where r (θ) is distance from the [illegible] at the time the suppression work began. If, however, [illegible] edge of the fire, then

[illegible]

Figure 5 shows examples of final fire shapes computed [illegible] tactics are illustrated in [illegible] shows the result of attacking the head fire [illegible] result of attacking the backing fire first.

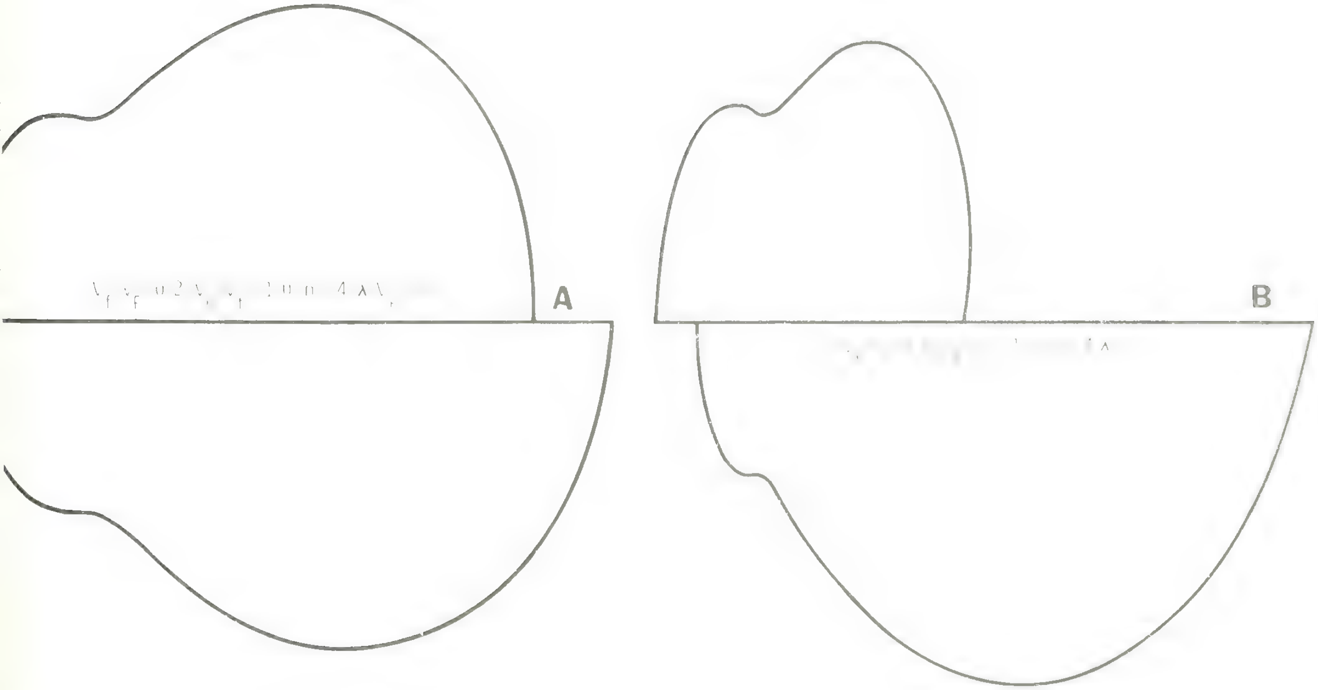
The time required [illegible] and 10:

[illegible]

where [illegible] is given by equation 3.

The total burned area [illegible]

[illegible]



[illegible]

Table 3.--Time required to contain a fire for two suppression tactics and various fire shape factors. λ/V_F is the ratio of suppression rate to forward rate of spread; V_f is the flanking rate of spread and V_B is the backing rate; n is another shape parameter (see fig. 1). Entries in table are (λ x containment time/initial perimeter), so are numerically equal to the final perimeter/initial perimeter

		Tactic 1 : attack backing fire first						Tactic 2 : attack head fire first					
		n = 1		n = 2		n = 4		n = 1		n = 2		n = 4	
λ/V_F	$\frac{V_f}{V_F}$ \ $\frac{V_B}{V_f}$	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
100	0.2	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00
	.4	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
	.6	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
	.8	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
	1.0	1.02	1.02	1.02	1.02	1.01	1.02	1.01	1.02	1.01	1.02	1.01	1.02
10	.2	1.13	1.13	1.12	1.12	1.12	1.12	1.06	1.07	1.05	1.05	1.04	1.04
	.4	1.14	1.14	1.13	1.13	1.13	1.13	1.08	1.09	1.07	1.08	1.06	1.07
	.6	1.15	1.15	1.14	1.15	1.14	1.14	1.10	1.12	1.09	1.11	1.08	1.11
	.8	1.17	1.16	1.16	1.16	1.16	1.16	1.13	1.15	1.12	1.14	1.11	1.14
	1.0	1.19	1.18	1.18	1.18	1.18	1.18	1.15	1.18	1.15	1.18	1.14	1.18
5	.2	1.30	1.30	1.28	1.28	1.27	1.27	1.13	1.14	1.10	1.11	1.08	1.09
	.4	1.32	1.32	1.30	1.30	1.29	1.29	1.17	1.19	1.14	1.17	1.12	1.16
	.6	1.35	1.35	1.33	1.33	1.32	1.32	1.22	1.26	1.20	1.24	1.18	1.23
	.8	1.39	1.38	1.38	1.38	1.36	1.37	1.28	1.33	1.26	1.33	1.24	1.32
	1.0	1.45	1.43	1.43	1.43	1.42	1.43	1.36	1.43	1.34	1.43	1.32	1.43
3	.2	1.61	1.61	1.57	1.57	1.54	1.55	1.25	1.26	1.18	1.20	1.14	1.17
	.4	1.66	1.66	1.61	1.62	1.58	1.59	1.32	1.36	1.26	1.31	1.22	1.28
	.6	1.74	1.72	1.69	1.69	1.65	1.66	1.42	1.50	1.37	1.46	1.33	1.44
	.8	1.84	1.81	1.79	1.79	1.76	1.78	1.56	1.69	1.51	1.67	1.47	1.65
	1.0	2.00	1.95	1.95	1.95	1.92	1.95	1.74	1.95	1.69	1.95	1.66	1.95
2.5	.2	1.83	1.83	1.76	1.77	1.73	1.73	1.31	1.33	1.23	1.26	1.17	1.21
	.4	1.90	1.89	1.83	1.83	1.78	1.79	1.41	1.46	1.33	1.40	1.28	1.36
	.6	2.01	1.98	1.93	1.93	1.88	1.90	1.55	1.65	1.47	1.60	1.42	1.57
	.8	2.17	2.13	2.10	2.10	2.05	2.07	1.74	1.93	1.67	1.90	1.62	1.88
	1.0	2.42	2.34	2.35	2.34	2.30	2.34	2.01	2.34	1.95	2.34	1.90	2.34
2.0	.2	2.28	2.28	2.16	2.17	2.10	2.11	1.43	1.45	1.31	1.34	1.23	1.27
	.4	2.40	2.38	2.27	2.28	2.19	2.21	1.57	1.65	1.45	1.55	1.37	1.49
	.6	2.59	2.55	2.45	2.45	2.36	2.39	1.78	1.95	1.66	1.87	1.58	1.81
	.8	2.91	2.82	2.76	2.76	2.66	2.71	2.10	2.44	1.98	2.38	1.90	2.34
	1.0	3.42	3.27	3.28	3.27	3.18	3.27	2.61	3.27	2.48	3.27	2.40	3.27
1.5	.2	3.72	3.72	3.42	3.43	3.24	3.26	1.70	1.74	1.48	1.54	1.35	1.41
	.4	4.04	4.01	3.68	3.69	3.47	3.50	1.96	2.10	1.72	1.89	1.58	1.77
	.6	4.60	4.46	4.18	4.18	3.91	3.98	2.38	2.75	2.12	2.54	1.95	2.40
	.8	5.66	5.40	5.16	5.16	4.82	4.98	3.15	4.07	2.84	3.88	2.63	3.74
	1.0	7.93	7.45	7.32	7.45	6.93	7.45	4.77	7.45	4.38	7.45	4.13	7.45

[illegible]

[illegible]

[illegible] ships:

[illegible]

where

[illegible]

where values of (P /r (0)) are tabulated in table 1.

Note, however, that while the values given in table 1 are limited to the range [illegible]

[illegible] spread [illegible] tactic [illegible] equation 19, and [illegible] below three, the ratio [illegible] than one under tactic 1. Under tactic 2 the ratio is generally greater than one when [illegible]

From this sensitivity analysis we can reinforce conventional wisdom with regard to the two most important [illegible] containment [illegible] indirectly, [illegible]

we have established a means of quantifying the influence of these factors for the purpose of [illegible]

CHANGING TACTICS:
INDIRECT ATTACK ON RAPID HEAD FIRE

In the mathematical formulations above, a necessary condition for successful containment of a fire is that $\lambda > V_F$, or that the rate of suppression must exceed the forward rate of spread of the fire. But as every firefighter knows, this condition can be violated and yet the fire can be contained. If the head fire is advancing too rapidly to be contained by suppression action at the edge of the fire, in many cases the firefighting team will construct a "fire break" or barrier ahead of the advancing fire to stop its forward progress. Then working against the flanking fire either from the forward or the rear direction, the encirclement can be completed by work at the edge of the fire.

In figure 4 we sketch such an attack against a rapidly advancing head fire. The first step, shown in figure 4a, is to establish a barrier ahead of the fire, perpendicular to the direction of maximum rate of spread. When the fire reaches this barrier, as shown in figure 4b, work proceeds back toward the flanks of the fire. When the crew meets the advancing edge of the fire, as shown in figure 4c, work can proceed at the edge of the fire from that point on around to the rear, since the perpendicular rate of fire spread at the point of meeting is less than the rate of suppression.

For the purpose of carrying out a mathematical analysis of this tactic, we idealize the situation as follows:

(1) Work proceeds symmetrically, by two crews, and the rate of line construction is everywhere the same ($=\lambda$, as before).

(2) At the instant the forward edge of the fire reaches the perpendicular barrier, the crews change direction of work and proceed in straight lines back toward the fire flanks.

(3) The direction chosen for the second straight segment of barrier line is such as to bring the crew into contact with the edge of the fire in a direction tangent to the instantaneous fire boundary.

Clearly there is a mathematical solution to the problem of choosing the best distance (a) ahead of the fire front, and likewise a best (probably curved) path to follow to bring the crews into contact with the edge of the fire. Such a solution would be interesting as a mathematical problem, but of little practical significance. The idealization chosen is, hopefully, a compromise between mathematical perfection and realizable practice. It should be noted that this idealization is not tied to any particular method of line construction (machine-aided hand line, hand line with back firing, machine construction, explosive construction, etc.)

The use of the tactic as described would be rare in the United States and is infrequent in the Soviet Union. But, when conditions permit its use with due regard for crew safety, the reward in terms of burned area and time of control can be substantial in some cases.

As the procedure is outlined above, for any given set of fire shape parameters (V_f/V_F, V_B/V_f, and n) and given value of λ/V_F, the final area and perimeter are completely determined by the choice of a value for the distance (a) ahead of the fire at which the initial barrier is constructed. We normalize this distance by the initial distance from the point of ignition to the front of the fire, $r_o(0)$.

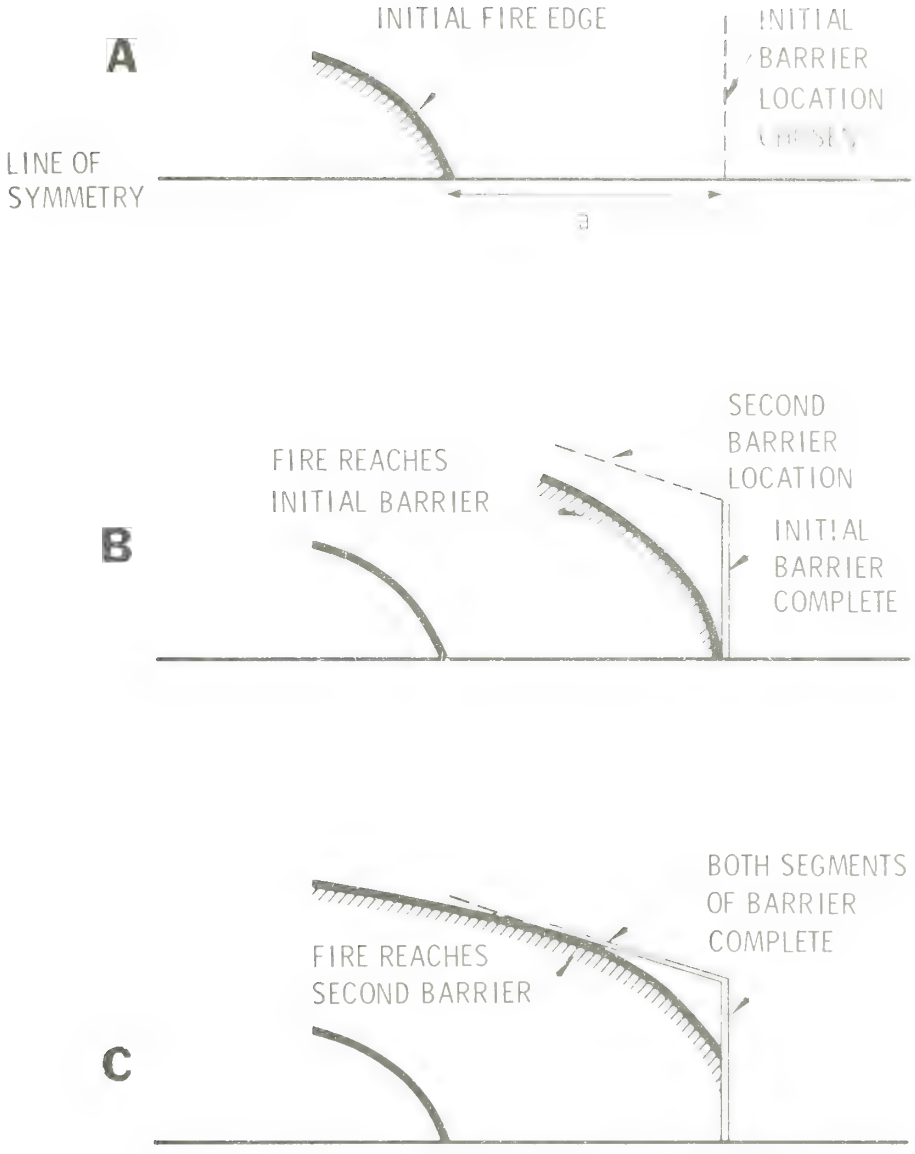


Figure [illegible].--[illegible]

Clearly a best choice exists for the value of "a". If "a" is [illegible], the fire will reach the barriers very quickly, and contact [illegible] the [illegible] at a position near the line of symmetry; if [illegible] violated, control will not be possible. If "a" is too large, the initial barrier will be unnecessarily long and much time will be wasted [illegible] made; indead if "a" is sufficiently large, the second barrier will [illegible] the fire at a point to the rear of the fire flank, resulting in much unnecessary burned area.

Table 4.--Values of burned area/initial area and final perimeter length/initial perimeter length when the suppression tactic is to build barriers ahead of the fire as sketched in figure 4. Also, tabulated is the first barrier distance ahead of the fire (a) divided by $r_0(0)$, the distance from the point of ignition to the head of the fire. λ is the rate of suppression, V_F the forward rate of spread, and V_f the flanking rate; n is a fire shape parameter (see figure 2)

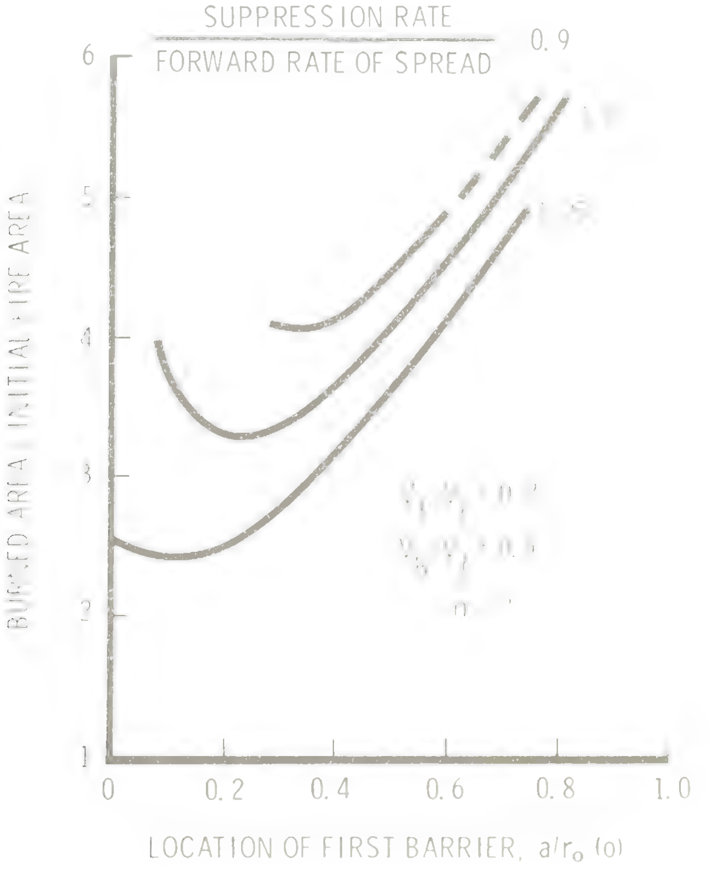
$\frac{\lambda}{V_F}$	$\frac{V_f}{V_F}$*	Minimum values of						First barrier location, $a/r_0(0)$					
		Burned area / initial area			Perimeter length / initial perimeter			For minimum burned area			For minimum perimeter length		
		n=1	n=2	n=4	n=1	n=2	n=4	n=1	n=2	n=4	n=1	n=2	n=4
2	0.1	1.72	1.54	1.42	1.36	1.25	1.17	0.04	<.02	<.02	0.06	0.05	0.03
	.2	1.87	1.67	1.55	1.41	1.30	1.22	.04	.04	<.02	.07	.05	.03
	.3	2.07	1.85	1.72	1.48	1.36	1.29	.05	.04	<.02	.07	.06	.03
1.5	.1	2.15	1.81	1.60	1.55	1.36	1.24	.10	.07	.04	.13	.09	.05
	.2	2.43	2.04	1.81	1.64	1.44	1.32	.10	.07	.04	.15	.10	.06
	.3	2.82	2.35	2.09	1.75	1.54	1.42	.12	.08	.04	.16	.11	.06
1.25	.1	2.66	2.10	1.77	1.75	1.48	1.31	.14	.09	.06	.19	.12	.07
	.2	3.11	2.43	2.07	1.88	1.59	1.42	.15	.10	.07	.22	.13	.08
	.3	3.78	2.92	2.48	2.04	1.73	1.55	.18	.13	.08	.25	.15	.08
1.0	.1	3.96	2.70	2.11	2.19	1.70	1.44	.34	.20	.11	.39	.23	.13
	.2	4.98	3.32	2.58	2.42	1.87	1.59	.38	.22	.13	.44	.25	.16
	.3	6.65	4.28	3.29	2.75	2.10	1.79	.45	.26	.15	.49	.28	.18
0.9	.1	5.34	3.21	2.34	2.57	1.86	1.52	.54	.29	.15	.59	.31	.15
	.2	7.13	4.09	2.96	2.93	2.08	1.70	.62	.32	.17	.66	.35	.19
	.3	10.3	5.54	3.93	3.44	2.40	1.96	.72	.37	.20	.76	.40	.21
0.8	.1	9.44	4.19	2.73	3.42	2.14	1.64	1.12	.47	.23	1.12	.47	.24
	.2	14.3	5.65	3.60	4.14	2.46	1.88	1.37	.54	.26	1.37	.55	.27
	.3	25.3	8.31	5.04	5.37	2.95	2.22	1.78	.65	.30	1.78	.65	.31
0.7	.1	41.0	6.88	3.54	7.10	2.73	1.87	3.50	.90	.40	3.50	.90	.40
	.2	116.0	10.5	5.12	11.7	3.33	2.23	5.80	1.10	.50	5.80	1.10	.50
	.3		18.2	7.89		4.36	2.77	>10	1.40	.60	>10	1.40	.60

* For all cases, $V_b/V_f = 0.5$

Table 3 present [illegible] perimeter for [illegible] forward rate of spread. [illegible] achieving the [illegible] the final perimeter length.

In[illegible] [illegible] ow values of burned and perimeter length achievable using this tactic. A comp[illegible] table 2 and 3 with [illegible] attack" tactic does not increase the burned area or extend the [illegible] significantly when [illegible] of di[illegible] head of the fire. [illegible] the tactic of approaching the fire from the back.

Figures 5 and 6 exhibit the sensitivity of burned area and final perimeter to the choice of first barrier location. The location of the first barrier to minimize burned area will result in a containment time not very different from the minimum value. Conversely, if the barrier is located to minimize containment time, very little area beyond the minimum will be burned. Figures 7 and 8 show graphically the sensitivity of the optimum barrier location to the rate of suppression and fire shape. The similarity of the curves in figures 5 and 7 and in figures 6 and 8 again illustrates that the criterion for optimization of the barrier location is not significant if the fire shape, suppression rate, and forward fire spread rate are known.



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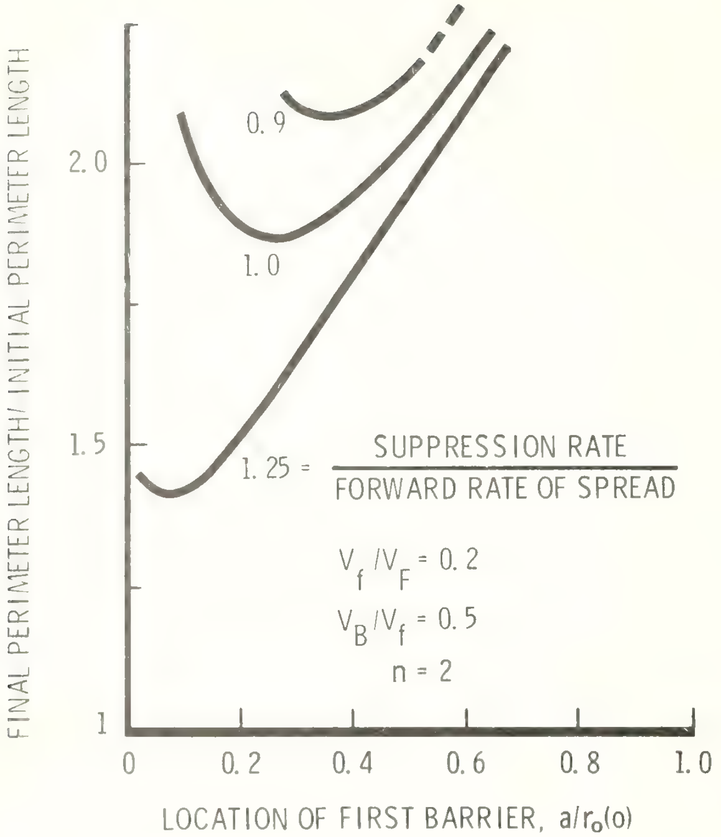


Figure 6.--Sensitivity of final perimeter to the choice of first barrier location.

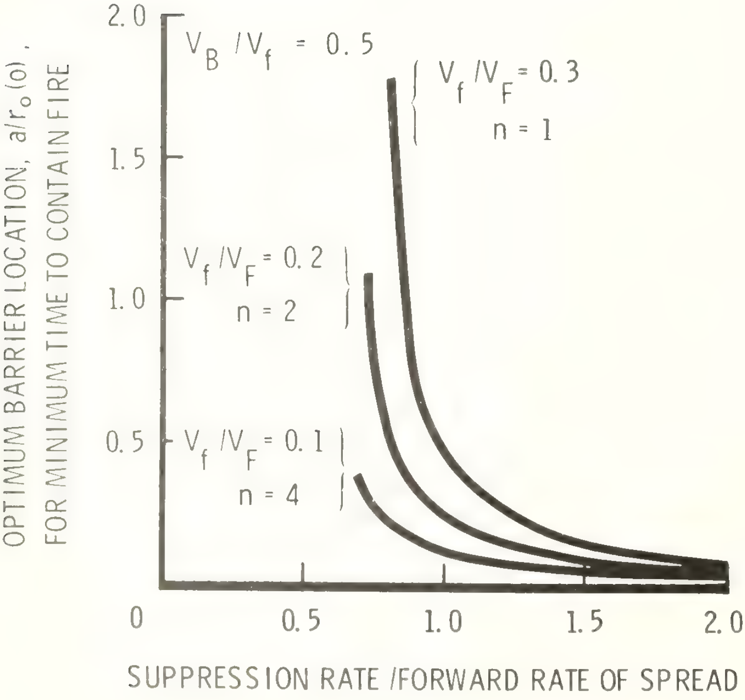
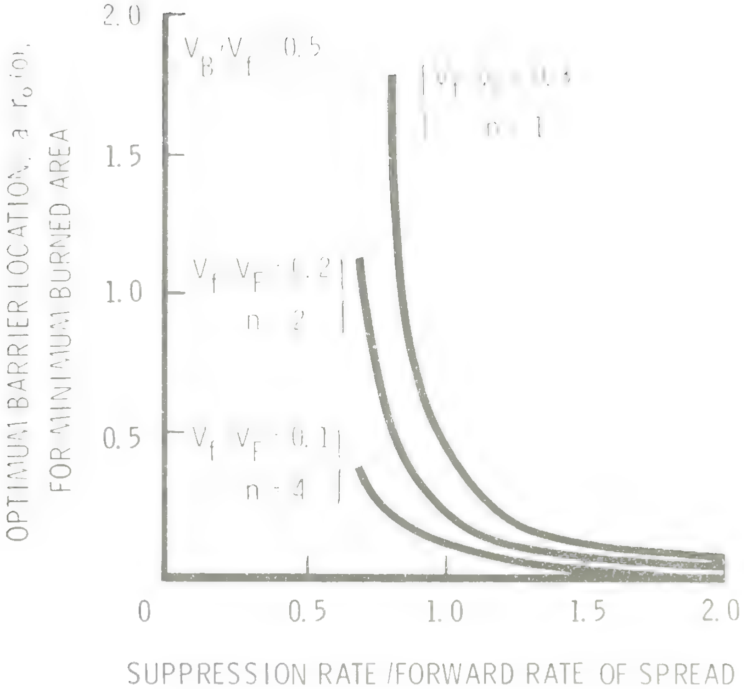


Figure 7.--Sensitivity of optimum (minimum burned area) location of first barrier to suppression rate and fire shape.

Figure [illegible].--[illegible]



But this series of figures also tell[illegible] a small "error" in barrier placement [illegible] are properly chosen. But [illegible] catastrophic miscalculation. For example, [illegible] the shape of the forward edge of the fire. [illegible] is [illegible] from either figure 7 or figure [illegible], [illegible] indicated. Such a choice would result in a [illegible] initial area, and a final perimeter [illegible] 1.0 [illegible]. However, if the value of the suppression rate had been [illegible] the forward rate of spread underestimated by a similar amount, we should refer to the curves labeled "0.9" in figures 5 and 6. On these curves, any value of a/r (0) less than 0.28 results in no solution. In other words, any barrier location closer than [illegible] critical value of 0.28 r (0) from the forward [illegible] sufficient time to the crew to achieve a "return" [illegible] edge of the fire.

Because of this sensitivity and the [illegible] for the first barrier location [illegible] "margin of safety" must be considered in the selection of the initial barrier location whenever [illegible] V_f. For this reason, table [illegible] perimeter ratio for the same conditions [illegible] location is chosen to be twice the [illegible] therefore, incorporates a "margin of safety" of 100 percent in the deviation from optimum. A comparison of the values in tables 4 and 5 reveals that the "penalty" paid for this margin of safety is not severe in most cases.

Table 5.--Values of burned area/initial area and final perimeter length/initial perimeter length when the suppression tactic is to build barriers ahead of the fire as sketched in figure 4. In this table, the barrier location, a, is chosen to be twice the value which minimizes the burned area using this tactic (see table 4). This "margin of safety" is introduced to accommodate the practical difficulty of estimating forward rate of spread and/or suppression rate to high accuracy

$\frac{\text{[illegible]}}{V_F}$	$\frac{V_f}{V_F}$*	n = 1			n = 2			n = 4		
		$\frac{a}{r_o(o)}$	Burned area	Final perimeter	$\frac{a}{r_o(o)}$	Burned area	Final perimeter	$\frac{a}{r_o(o)}$	Burned area	Final perimete
2.0	0.1	0.08	1.73	1.36	0.04	1.54	1.25	0.04	1.42	1.17
	.2	.08	1.88	1.42	.07	1.69	1.30	.04	1.56	1.23
	.3	.09	2.08	1.48	.08	1.86	1.36	.05	1.73	1.29
1.5	.1	.19	2.24	1.56	.14	1.88	1.38	.07	1.62	1.25
	.2	.21	2.52	1.65	.15	2.10	1.46	.08	1.84	1.34
	.3	.23	2.94	1.77	.16	2.43	1.56	.08	2.11	1.43
1.25	.1	.27	2.77	1.76	.17	2.15	1.49	.11	1.83	1.33
	.2	.31	3.26	1.90	.19	2.50	1.60	.15	2.16	1.44
	.3	.35	4.00	2.08	.26	3.12	1.78	.16	2.59	1.58
1.0	.1	.68	4.89	2.36	.40	3.15	1.81	.22	2.30	1.49
	.2	.76	6.20	2.64	.47	3.97	2.02	.26	2.85	1.66
	.3	.90	8.66	3.08	.52	5.00	2.26	.30	3.67	1.89
0.8	.1	2.24	19.0	4.72	.94	6.34	2.59	.46	3.37	1.82
	.2	2.74	36.4	6.49	1.08	8.53	2.99	.52	4.58	2.12
	.3	3.56	56.6	7.94	1.30	13.70	3.77	.60	6.49	2.52

* For all cases, $V_B/V_f = 0.5$.

SUMMARY

We have established a mathematical [illegible] suppression that can be used for economic [illegible] hose presented in this paper, analyses of costs [illegible] rganizations will be facilitated. [illegible] valuations are only possible using [illegible] road applicability can be [illegible] orthwhile.

Extension of the present analysis to include the effect of a variable rate of uppression is straightforward. [illegible] sing the basic formulation presented here. Such extensions may be the subject of uture studies.

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Albini, F. A., G. N. Korovin, and E. H. Gorovaya.
1978. Mathematical analysis of forest fire suppression. USDA For. Serv. Res. Pap. INT-207, 19 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

This paper presents a mathematical formulation of the construction of a containment perimeter for a wildland fire. The formulation permits the calculation of total burned area, final perimeter, and containment time, if the rate of growth of the fire can be specified as a function of time and position.

KEYWORDS: forest fire control, fire behavior model, fire management, computer programs.

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BALLOON LOGGING
IN THE
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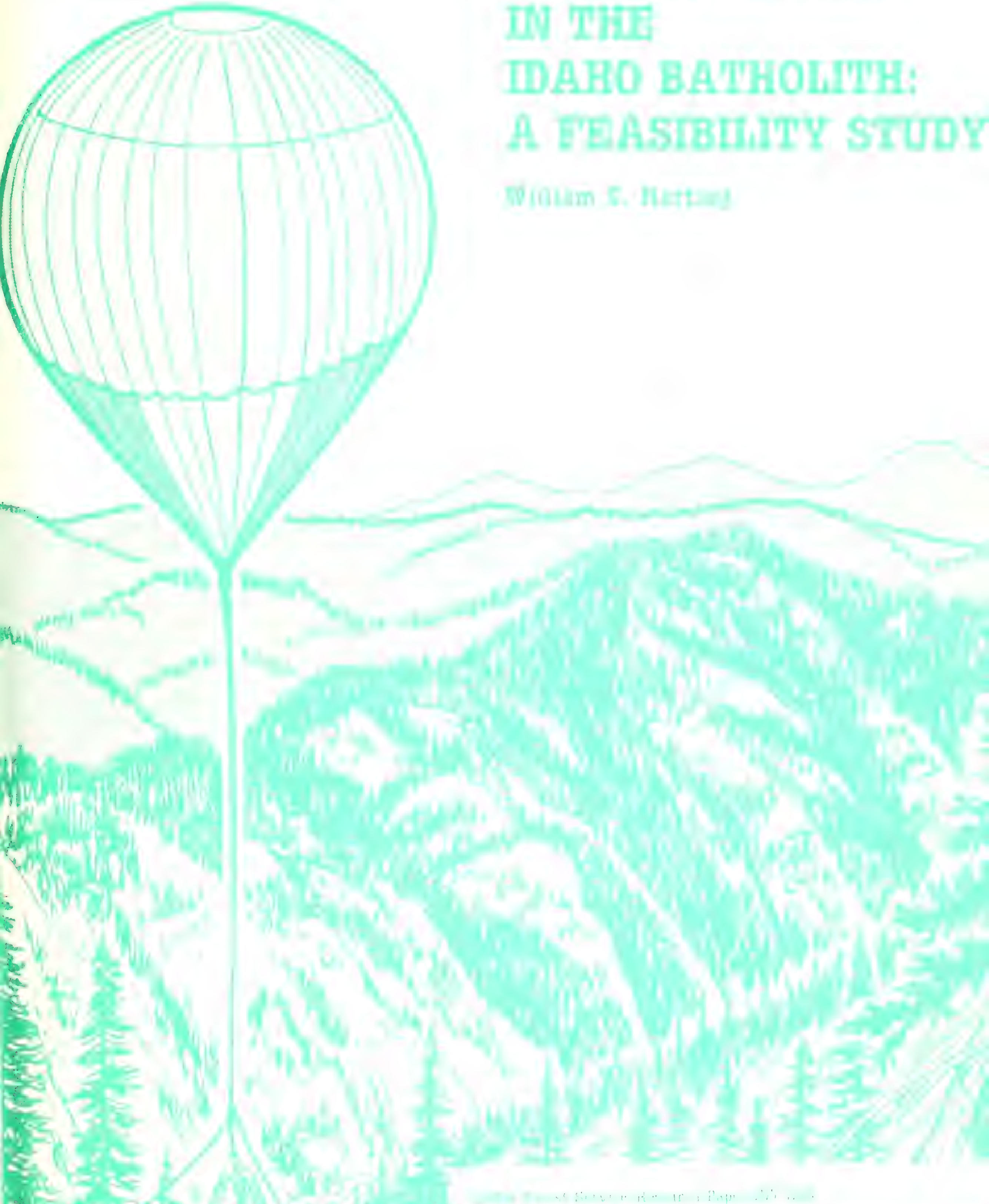
A FEASIBILITY STUDY

William S. Hartsog



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Research Paper INT-[illegible]
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BALLOON LOGGING IN THE IDAHO BATHOLITH — A FEASIBILITY STUDY

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RESEARCH SUMMARY

Experience has shown that road networks needed for conventional logging can lead to severe erosion in the Idaho Batholith. In an attempt to develop an environmentally acceptable logging system, in 1971 the Forest Service, USDA, in cooperation with Boise Cascade Corporation, began an experiment with balloon logging in Anderson Creek near Garden Valley, Idaho, on the Boise National Forest.

The balloon logging system resulted in far less environmental impact on the land as compared to conventional logging methods. This conclusion is based on observations both shortly after the area was logged and after several years had passed.

This sale proved the physical capabilities of logging with the balloon system in the Idaho Batholith area; however, the conditions are not ideal, with the steep, broken terrain and low timber volumes. A description of the equipment, the methods of operation, and problems with the system are included in the report.

An economic analysis of the logging is presented in the form of regression equations. Factors within the analysis include thousand board feet logged per acre, board feet per piece, pieces per productive hour, turns per productive hour, percent productive hours, and costs per thousand board feet.

INTRODUCTION

The Idaho Batholith comprises [illegible] terrain in central Idaho. Because experience has shown that roadbuilding in the Batholith can cause accelerated erosion rates and lead to mass instability problems, many stands of overmature ponderosa pine and Douglas-fir have not been harvested.

In an attempt to develop an environmentally acceptable logging system, in 1971 the Forest Service, USDA, in cooperation with Boise Cascade Corporation began an experiment with balloon logging in Anderson Creek near Garden Valley, Idaho, on the Boise National Forest. The selection of this system was based on projections (McIntosh 1968) of balloon yarding costs from tests conducted in British Columbia and reports from Bohemia Lumber Company's balloon logging operation in Deception Creek, Oregon, where an onion-shaped balloon proved successful.

Major objectives of this study are to evaluate environmental impacts, logging capability, and economic feasibility of balloon logging in the Rocky Mountain area. Gardner and others (1973) reported that this balloon logging experiment appeared to be environmentally acceptable based on short-term observations, was physically capable of logging the area within the restraints caused by terrain, and was marginal from an economic standpoint for logging in the Idaho Batholith.

The purpose of this summary report is to present a detailed analysis of the balloon logging costs, production data, and to evaluate the environmental effects of balloon logging after several years' observation. During August 1977 the balloon sale area was revisited in order to make a visual inspection of the environmental impacts as they appeared several years after the logging was completed. Photos were taken of the area and these showed that visual effects of the logging disappear rapidly where ground disturbance was minimized. This inspection covered roads, cut areas, landings, and streams.

ENVIRONMENTAL IMPACTS

The balloon logging system proved to be an effective logging tool from an environmental viewpoint. The 3,000 ft (914 m) maximum yarding reach with this system allowed the area to be logged from existing roads. This resulted in far less damage to the logged area (Anderson Creek watershed), as compared to logging done in previous years with cat-and-jammer logging systems and the associated dense network of roads. The scars from the old logging and roads are still readily apparent, even though it has been over 20 years since much of the logging took place. Figure 1 shows an extreme example in the northern part of the Idaho Batholith of how an area looks when closely spaced roads are required to facilitate the logging method. In contrast, figure 2 shows an example of the appearance of an area shortly after being logged with the

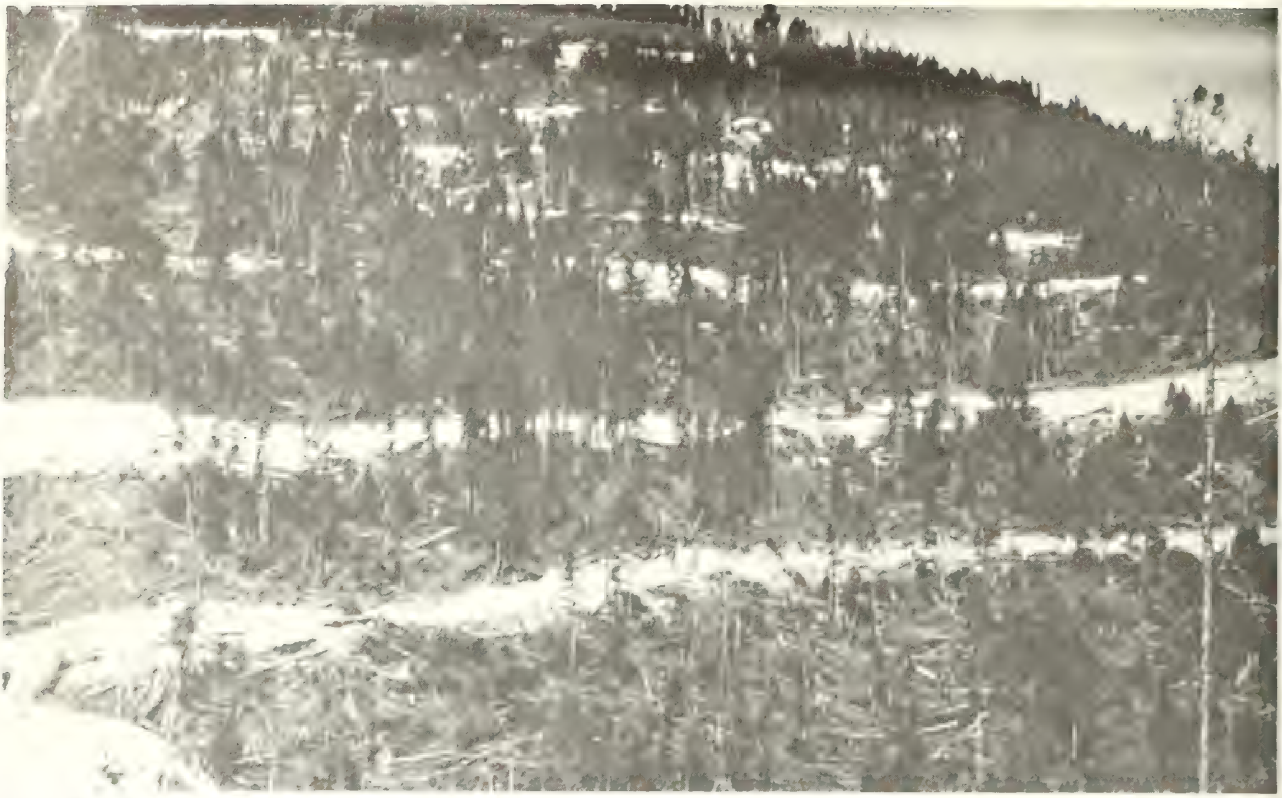


Figure 1.--An extreme example of closely spaced roads to facilitate the logging system in the Northern Batholith.

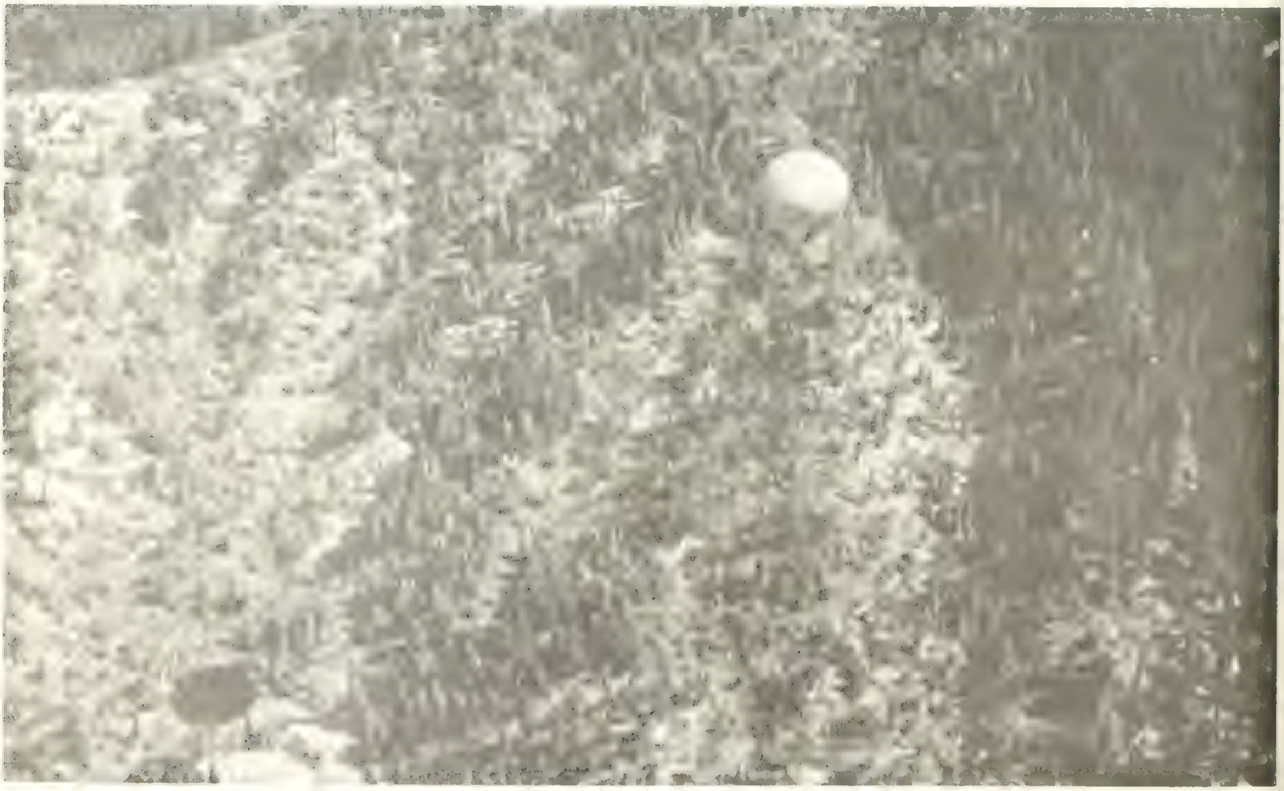


Figure 2.--An area logged with the balloon logging system.

Figure 3.--[illegible]

balloon system. The esthetic advantages of balloon logging are readily [illegible] the air or on the ground as there are few roads left on the [illegible] conventional logging methods. The visual [illegible] soon after logging and after several years have passed since the logging took place (fig. 3).

Lifting logs vertically with the balloon and flying them to the landing allows any cutting method to be used. On this sale, an overstory removal harvesting method was used with a minimum diameter specified, in order to release the understory. Minimum diameter varied depending on the unit, but most units had a 13-inch (33-cm) minimum diameter. Very little damage to the understory resulted, and the majority of this damage occurred during the felling operation. A few limbs were broken by the main and haulback lines and flying logs, but this damage was minimal.

A buffer strip of timber was left uncut, adjacent to stream channels in each logging unit. This was an effective method of protecting the stream, and the only apparent damage was due to a few logs being accidentally dropped into the creek during the yarding operation. Any debris from the logging was removed and the creek shows no effects from the logging. Figure 4 shows a typical reach of Anderson Creek as it was in August 1977.

Landing construction was a source of ground disturbance. In order to minimize this disturbance, many of the landing areas were less than one-half acre (0.2 ha) in size, or the road surface was used for a landing area (fig. 5). A bedding area (fig. 6) was constructed in the Cow Creek subdrainage for tying the balloon down during severe storms or for maintenance work on the balloon. This was the only sizable embankment constructed for the balloon logging operation, and some erosion resulted--the majority being during a high intensity rainfall shortly after construction. The gullies from the erosion have been vegetated and have stabilized as shown in figure 7.

The reduction in the density of roads with the balloon system leaves the land manager with limited access to manage the land. This can be a problem especially where fire, disease, or insects are a threat because proper slash treatment is difficult due to poor access. This is not to say that proper slash treatment cannot be accomplished, but that the high costs of treatment must be considered as an extra cost in the balloon system as compared to logging systems using a more dense road network. Regeneration and other management functions also will be more difficult and expensive because of the limited access provided by the balloon logging road system.

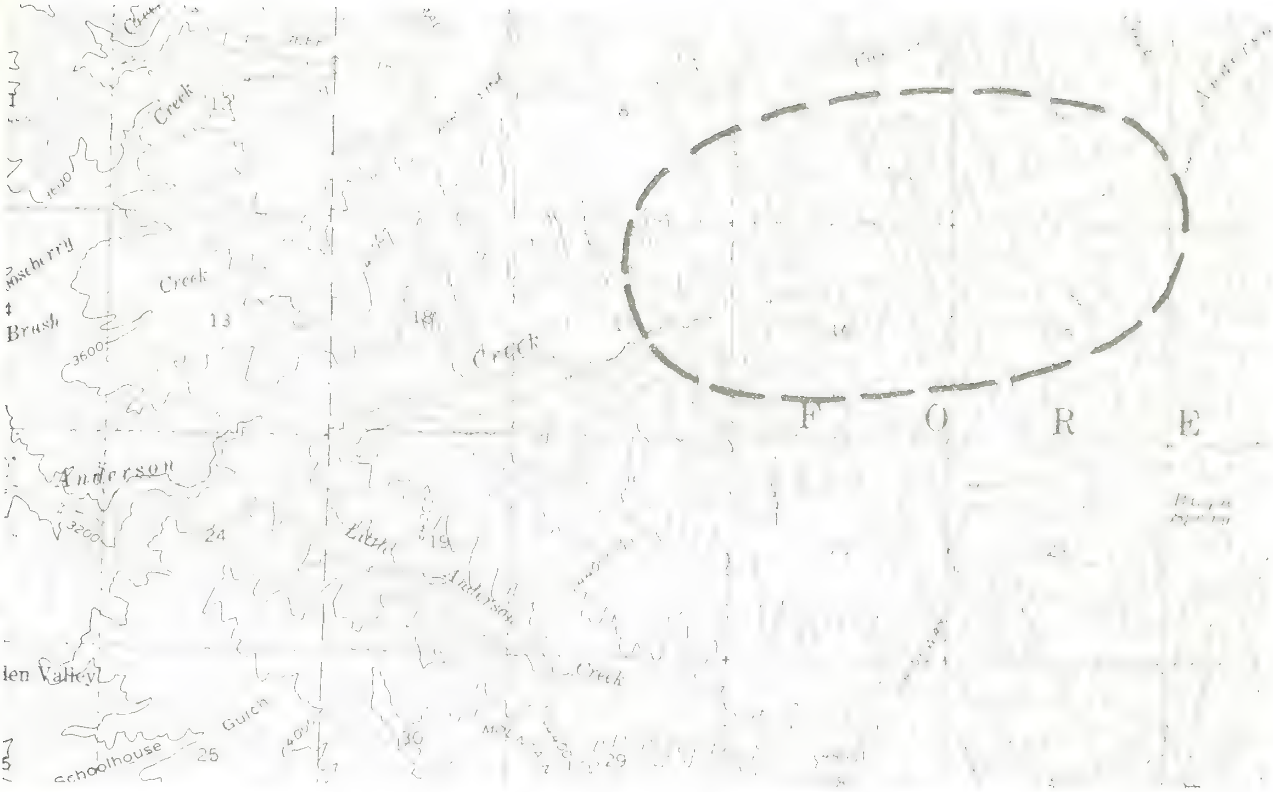
PHYSICAL CHARACTERISTICS AND LOGGING CAPABILITIES

This sale proved the physical feasibility of logging with a balloon system in the Idaho Batholith area; however, the conditions are not ideal. Steep slopes, generally 45 to 90 percent, made working conditions difficult for the riggers, fellers, and choker setters. The highly dissected drainages made frequent cable road and layout changes necessary in order to reach the logs. Figure 8 shows the severity of the terrain on a contour map of the logged area.

The main piece of equipment for the half-million-dollar (1971 cost) yarding system was an onion-shaped, Dacron-neoprene fabric balloon which is 113 ft (34.4 m) in height and 105 ft (32 m) in diameter. The 560,000 ft^3 (15,857 m^3) helium-filled balloon had a net lift of 22,500 lb (10,206 kg) shortly after inflation. This lift varies considerably with elevation and temperature. (Temperatures in the Garden Valley area of Idaho range from below zero (-17.8° C) to above 100° F (37.8° C)). On cold mornings when the temperature was below freezing, decreased lifting capacity slowed the yarding operation considerably. The lifting capacity of the balloon is also greatly reduced by even a thin covering of snow or ice. A heavy snow can cause the balloon to tear due to the snow load or from the rebound when a snow load slides from the balloon. A tear did result from a sliding snow load and the resulting quick load release. The snow conditions at the logging site required that the balloon be stored for 3 or 4 months during each winter. Storage is a problem, as there is no economical way to deflate the balloon and store the gas. Snow removal was a continual maintenance burden for the logging company during winter bedding of the balloon (fig. 9), but it was the most economical solution since enough helium to fill the balloon cost approximately $25,000.

A very small amount of leakage occurred during normal operations, but this was not a problem and was within the expected loss estimates. The balloon's reflective aluminum surface was repainted during the 3-year sale in order to prevent excessive weathering of the fabric and to control temperatures caused by radiation from the sun.

Wind affects yarding in proportion to velocity, with the operation being considerably slower as the limiting operable velocity of approximately 25 mi/h (40 km/h) is approached. Variable winds are also troublesome even at low wind velocities due to the problems with landing loads and positioning over the logs for hooking chokers.


Creek
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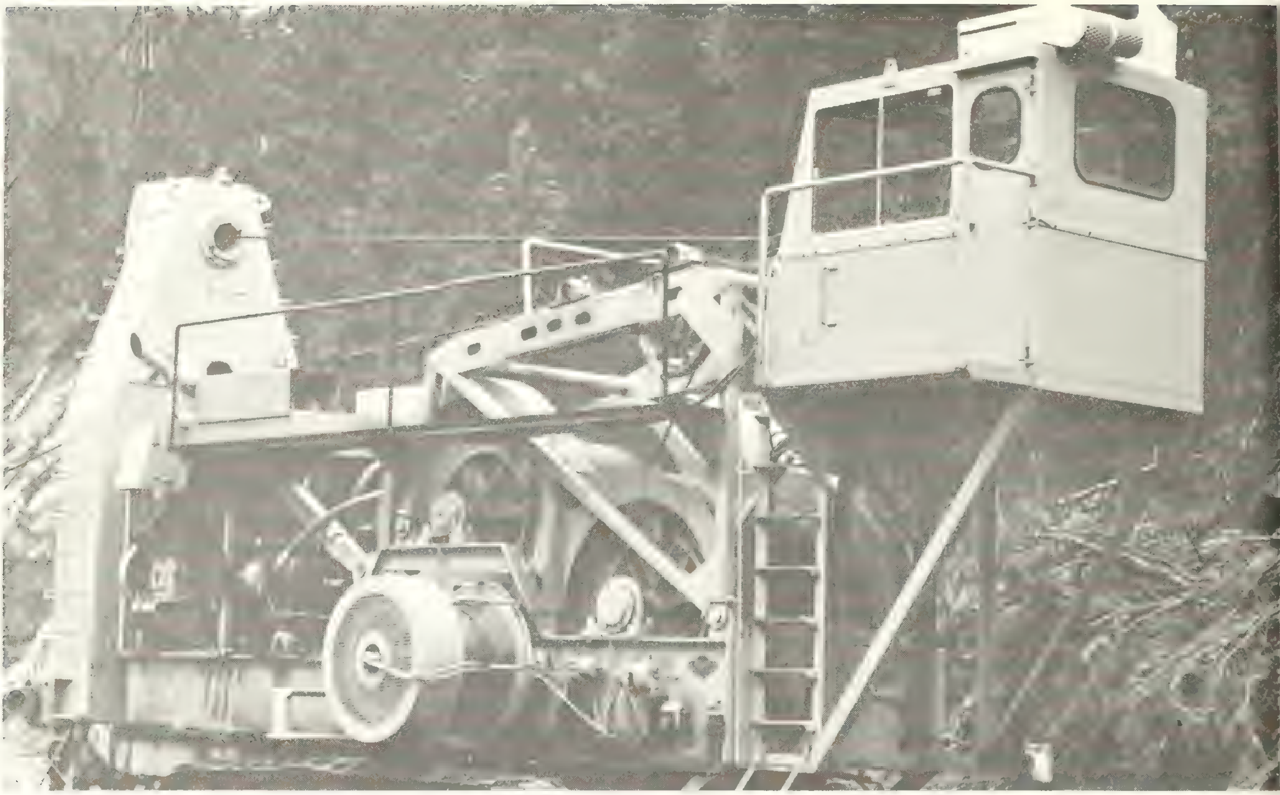


Figure 10.--Washington Model 608A yarder.

The yarder (fig. 10) was built by Washington Iron Works for the balloon logging system. Aero Yarder, Model 608A, has hydraulic interlocking drums with a mainline capacity of 5,500 ft (1,676 m) and haulback capacity of 7,000 ft (2,134 m) with 1-inch (2.54-cm) cable. The weight of the yarder is approximately 160,000 lb (72,575 kg) with a tracked undercarriage. Hydraulic problems and planetary gear problems occurred during the first year's operation, but the newly designed yarder performed satisfactoril during most of the last two logging seasons. An HD-21 tractor equipped with a large capacity hydraulic winch was used for transporting the balloon. The balloon was tethered to this tractor during maintenance and moving operations.

A schematic of a typical yarding layout for the sale is shown in figure 11. The figure illustrates the continuous cable system with the balloon providing a lifting force to fly logs from the stump to the landing. Location of the 5/16-inch (0.79-cm) strawline used for restringing the mainline is also shown. Figure 12 shows the operations schematic for a typical yarding turn.

The yarding turn starts with the balloon leaving the landing area unloaded. The balloon's buoyant force provides a portion of the power to move the system out to the felled logs. When the balloon is over the logs, tension is applied to the mainline and haulback to pull the balloon down so the tagline can be reached by the choker setters (fig. 12A). The chokers have been preset on the load of logs so that the load can be quickly hooked to the tagline and the men can move clear of the area. The choker setters then radio the machine operator that the load is hooked and ready to yard The lines are slacked so the balloon rises nearly vertically to clear the understory and the yarder begins pulling in the mainline while simultaneously slacking the haulback (fig. 12B). As the logs approach the landing area, the rate of travel is slowed to minimize swinging of the load and the lines are tensioned in order to set the logs on the landing area (fig. 12C). The chokers are unhooked from the logs and flown back to the choker setter as the cycle starts again.

The steep slopes and narrow [illegible] landing areas. Availability of [illegible] sale units; thus, the landings dictated much of the sale layout. Fortunately, the balloon system layout is not further limited by cable deflection requirements, the only requirement being that the main and haulback lines do not rub the ground. Small landing size is a safety problem because the log deck can quickly become a jackstrawed maze of logs when the loader used for clearing the log landing area is temporarily out of service. This makes the unhooker's job especially dangerous during the unhooking operation because of the possibility of shifting logs. In general, safety is decreased when the landings are small because of the increased congestion of men and equipment. Production is slowed with small landings since the swinging load of logs has to be brought into the landing more slowly for adequate control in setting the logs down on a small area.

The tagline, to which the chokers are attached, was varied in length as the terrain dictated. The longer length tagline allows the chokers to reach the ground with less effort expended in pulling the balloon down. However, the longer tagline caused the chokers and logs to swing more than a shorter tagline, thus taking more time to position the chokers for hooking and unhooking. The optimum length for the tagline was judged by the crew depending on wind, terrain, and logging set configuration, and tagline length could vary at each cable road location.

The choker setter's job proved to be difficult for several reasons. The terrain is steep, especially in some of the draws where slopes of 90 percent are encountered. This made dragging the tagline difficult and scrambling from the area below the flight path of the logs strenuous. It is particularly important from a safety standpoint to be clear of the logs to avoid becoming entangled with the load or being hit by a falling log or limb. Summer temperatures (sometimes around 100° F (37.8° C)) and fall snows and rains made the choker setter's job even more arduous.

Yarder operators had to be conscientious and skillful to keep the overall operation safe and efficient. Particular skill and quick thinking are required if a line breaks or a stump pulls loose because the balloon builds up a large inertial force with a few seconds of free flight. The balloon should be slowed gradually with the cable braking system. Locking the brakes on the yarder drums could upset the yarder or snap the cable when the balloon comes to the end of the slack in the cable.

Rigging the balloon system as an inverted standing skyline was tried in order to extend the system reach to over 5,000 ft (1,524 m). This system used the mainline as a standing skyline (nonmoving) and the carriage was inverted on the skyline (lifting the skyline rather than pulling it down) because of the balloon's lifting force. The carriage traveled along the skyline with the balloon pulling it uphill and the haulback line pulling the carriage and the logs downhill to the landing. The method was abandoned after 2 or 3 days because whipping and sawing of the skyline and haulback against each other caused rapid cable wear.

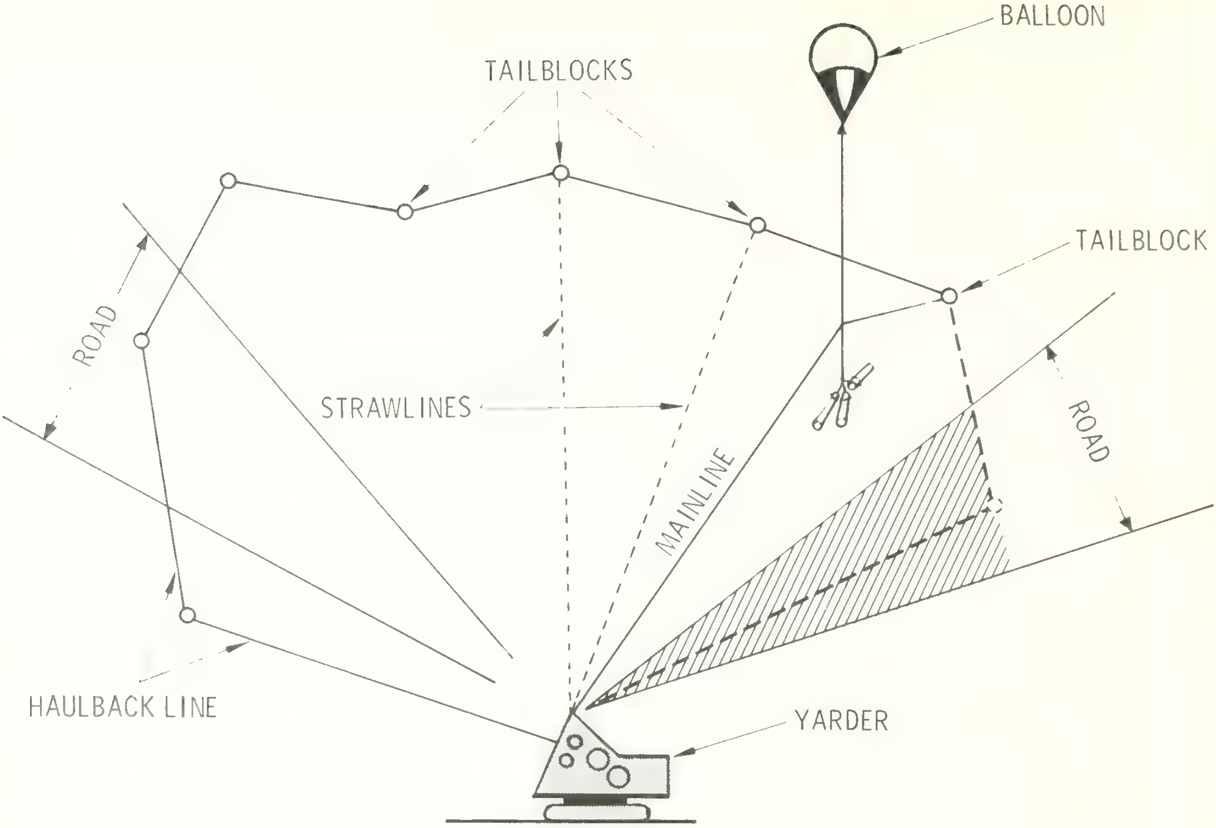


Figure 11.--Typical balloon unit and layout.

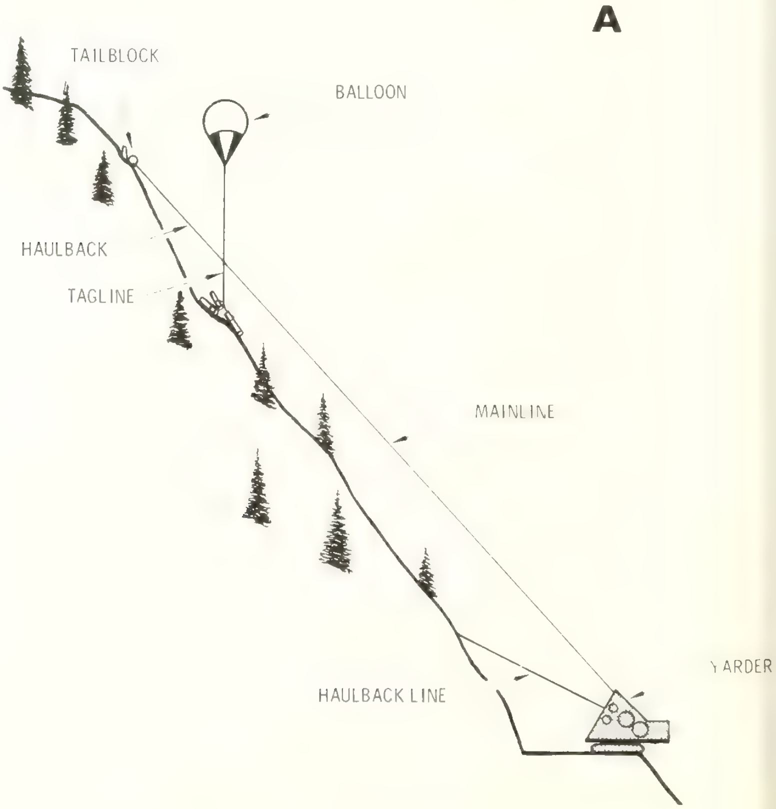
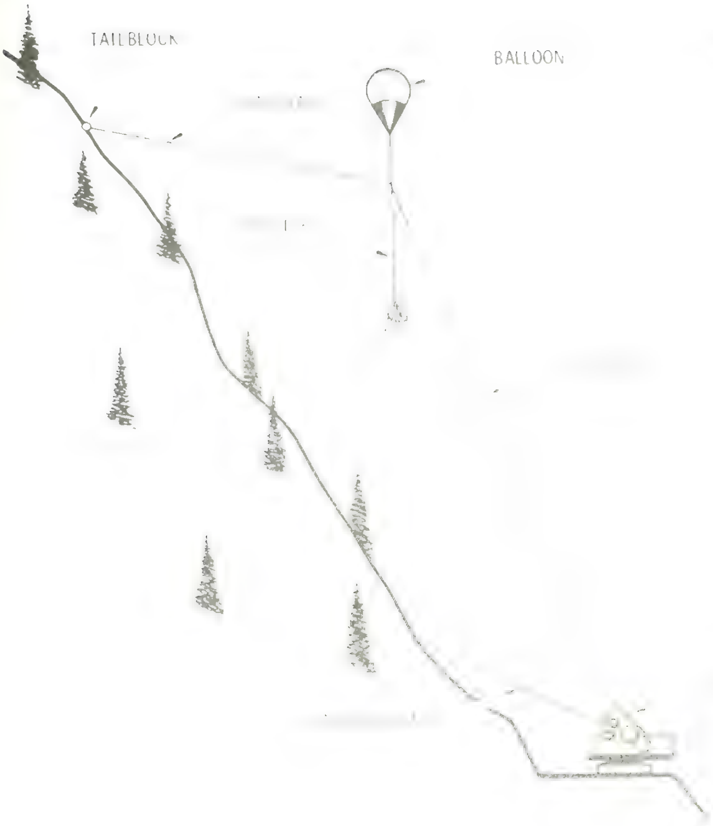


Figure 12.--Operations schematic of balloon logging system when the balloon is (A) over the logs, (B) logs are in the air, and (C) logs are at the landing.



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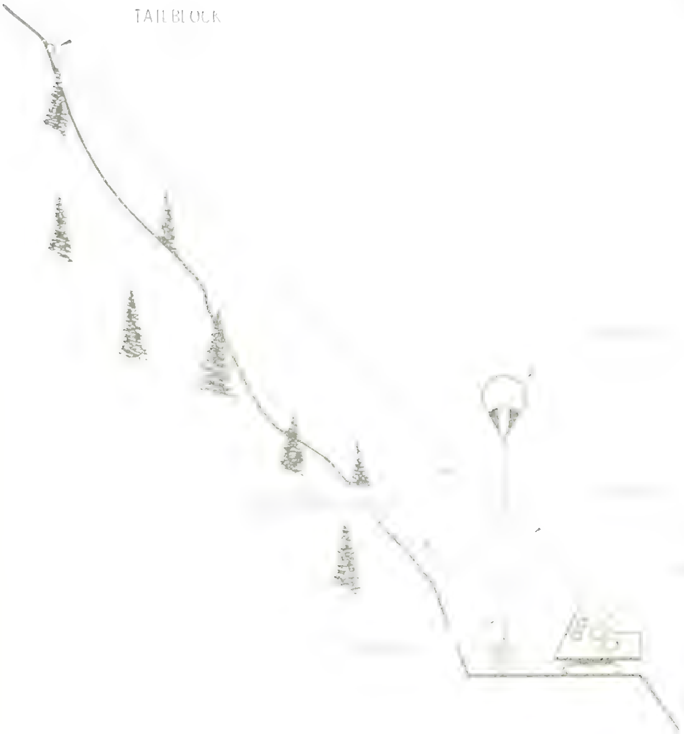


C

ECONOMIC FEASIBILITY

The balloon system has proven to be acceptable from an environmental viewpoint and also has demonstrated the physical capability to log in the Idaho Batholith area. The final test for a viable logging system is its economic feasibility. The balloon system economic feasibility was tested under a specific set of timber stand, harvesting, and terrain conditions in the Idaho Batholith. Unfortunately, balloon logging cannot be compared to conventional logging economics since these methods cannot be used to log terrain similar to the Anderson Creek site due to physical or environmental limitations It is believed that this economic analysis will prove useful for assessing balloon logging feasibility for the Rocky Mountain area in general.

The first step in the economic analysis was to plot production per hour versus tim in days to see if a learning period could be identified during the startup of the syste Cumulative plots of turns per productive hour (fig. 13) and pieces per productive hour (fig. 14) were used because of the high variability in daily production rates. The slopes of the line segments on the graphs indicate that production rates were not time dependent. This is not surprising in view of the circumstances involved on this timber sale. Boise Cascade had sent the crews to another balloon logging job on the West Coast to be trained for the balloon system of logging. Operators were selected that ha experience on similar equipment used for cable logging. Supervisory personnel from Bohemia Logging Company (a company with several years of experience with balloon loggin were on hand during the startup and initial shakedown of the system.

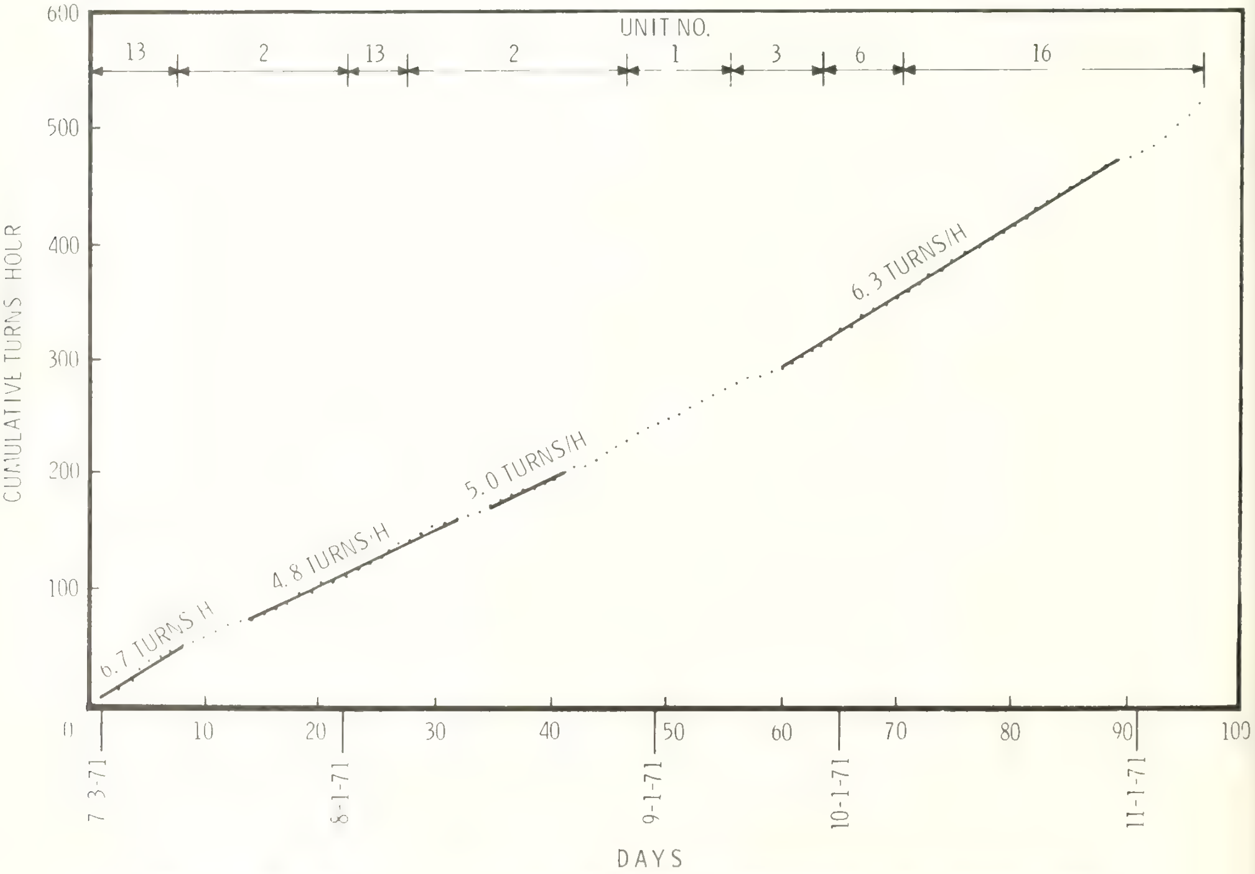
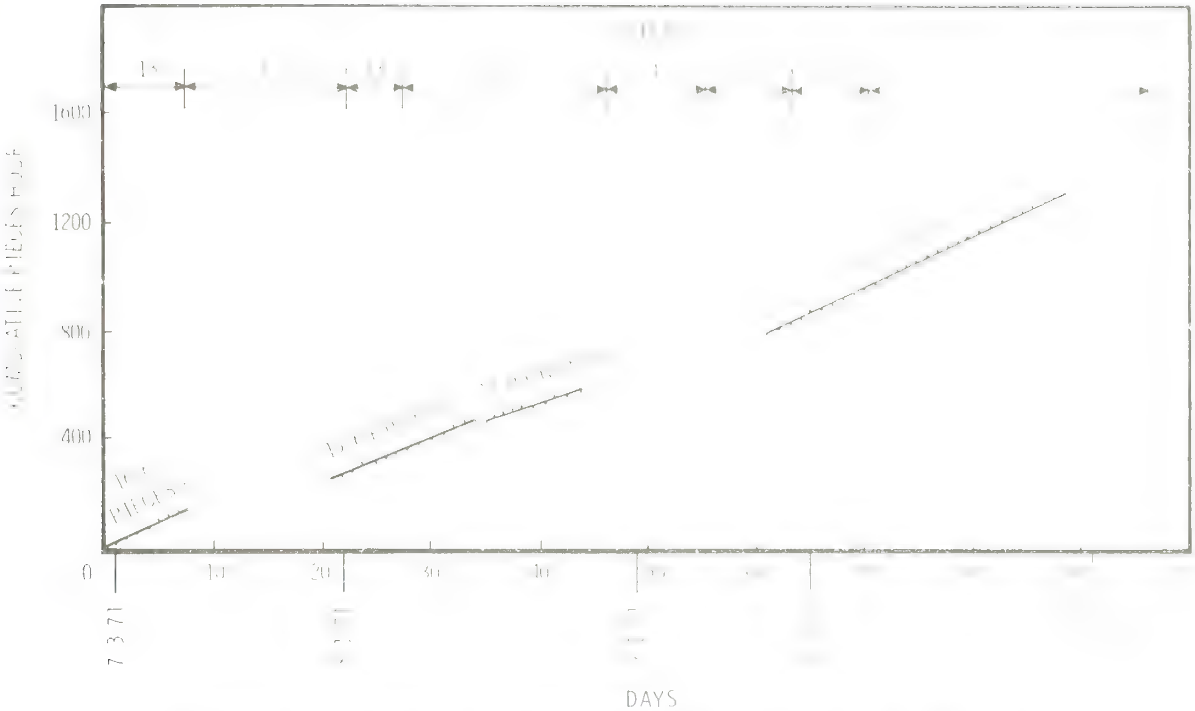


Figure 13.--Turns per productive hour (cumulative) vs. date, unit.



[illegible]

During 1971, gross data were collected on each [illegible] tion included M bd.ft. logged per acre (V), bd.ft. per piece (B), [illegible] hour, pieces per productive hour, percent productive hours (P), and costs per M bd.ft. (C). Table 1 shows these data for the units that were either completed or had substantial volumes of timber removed. The following regression analyses on these data, based on unit averages, explains much of the variation in costs and production.

Costs in dollars per M bd.ft. were supplied by Boise Cascade's accounting department. When total yarding cost per M bd.ft. (C) was used as the dependent variable and regressed on average piece size (B = bd.ft./piece), the resulting regression equation was

$$C = 92.77 - 0.1564B \text{ or in metric terms} \qquad (1)$$

$$C\left(\frac{\$}{m^3}\right) = 20.50 - 7.659B\left(\frac{m^3}{piece}\right)$$

with $R^2 = 0.5095$.

With volume per acre (V) as the independent variable

$$C = 61.89 - 3.458V \text{ or in metric terms}$$

$$C\left(\frac{\$}{m^3}\right) = 13.51 - [illegible]V\left(\frac{m^3}{ha}\right)$$

and the $R^2 = $ [illegible]. Multiple regression using [illegible] independent variables yielded the equation

$$C = 101.9[illegible] - [illegible]B - [illegible]V \text{ or in metric terms}$$

$$C\left(\frac{\$}{m^3}\right) = [illegible] - [illegible]B\left(\frac{m^3}{piece}\right) - [illegible]V\left(\frac{m^3}{ha}\right)$$

with an $R^2 = 0.9851$.

Table 1.--*1971 data--balloon logging*

Unit #	(V)[1] Volume M bd.ft./acre (m³/ha)	(B) Piece size bd.ft./piece (m³/piece)	(C)[2] Yarding cost $/M bd.ft. ($/m³)	Turns per productive hour	Pieces per productive hour	(P)[3] Percent productive hours
1	11.0 (123)	350 (1.58)	38.97 (8.61)	5.02	11.34	76.9
2	6.3 (70)	236 (1.07)	59.73 (13.20)	4.14	11.42	63.7
3	5.0 (56)	259 (1.17)	65.77 (14.54)	4.59	11.35	59.7
14	7.3 (81.6)	192 (0.87)	63.70 (14.08)	[4]	[4]	[4]
13	11.9 (133)	216 (0.98)	49.62 (10.97)	5.89	16.33	72.3
16	13.0 (145)	293 (1.33)	37.10 (8.20)	6.35	19.22	69.5

[1] Average volume harvested on the unit in thousand board feet per acre.
[2] The cost in dollars per thousand board feet for moving the logs from the stump to the landing (this includes balloon yarding, changing cable roads, landing costs, as well as costs for yarder downtime).
[3] Total yarding hours divided by total hours logged by yarder times 100.
[4] Data were not collected as this was the first unit logged on the sale.

Equation (1) shows that costs decrease as average piece size increases with this single variable explaining approximately one-half of the cost variation. Average piece size is used by many logging companies as one criterion on which to estimate costs of logging. From a physical standpoint, it also is reasonable to expect that costs would be lower when fewer pieces had to be handled per M bd.ft. of production.

In equation (2), volume per acre explained 83 percent of the variation in cost per M bd.ft. This relationship shows that volume per acre is the most important factor for predicting the cost of balloon yarding. At first glance, volume per acre seems to explain more of the cost variation than would be expected. Further analysis yielded a relationship between percent productive hours (P) and volume per acre

$$P = 53.50 + 1.58V \text{ or in metric terms} \qquad (4)$$

$$P = 53.50 + 0.1413\left(\frac{m^3}{ha}\right)$$

with an $R^2 = 0.6793$. This equation shows that the percent productive hours increases as the volume per acre increases. Based on field experience, it is reasonable to expect hat the number of road changes and percent down time for moving [illegible] he number of logs yarded on a given logging set increased. [illegible] reased $1.568 for each 1 percent increase in percent [illegible] ion (5) where cost was regressed on percent productive time:

$$C = 157.50 - 1.568P \text{ or in metric terms} \quad (5)$$

$$C = 34.81 - 0.3466P$$

nd $R^2 = 0.7263$. This relationship quantifies the cost of nonproductive time on this ogging operation.

Equation (3) yields a simple but useful relationship for predicting yarding costs ased on both volume per acre and piece size. These two variables should provide a good stimate since they explain 98 percent of the variability in cost based on the 1971 ogging data. It should be kept in mind that equations (1) through (5) should be used hen the variables are within the range of the data given in table 1, and any extrapolaion should be used with care.

These relationships based on gross data quantify factors that affect balloon loging and should be followed through with a larger range of data so that the prediction quations' range can be extended. Also, the equations should be verified by data from ther balloon logging sites. It is expected that these prediction equations would not e as good for other areas since there are many factors which affect logging costs that re not included in the equations. These factors can be more or less constant at one ogging site, but vary greatly between logging sites. Examples of some of these factors re local wage rates, fuel costs, weather, terrain, timber type, and harvesting techique. Another factor to keep in mind when using the cost figures is that they should e escalated for inflation because they are based on 1971 cost figures.

As shown in table 2, balloon yarding costs ranged from $42.44 to $54.49 per M bd.ft. f the site had been logged with a skyline (elevated cable) yarding system, costs would ave been about $20 per M bd.ft. Not included in the costs of skyline yarding is the ost of the extensive road system required, which would have raised total costs onsiderably.

Yearly average cost and production figures did not vary greatly. It was hoped that osts would decrease from year to year as experience with the balloon system was gained, ut this was not the case. Production did increase in the number of pieces per hour, ut the average piece size was smaller during the last year. Some of the more difficult arding chances were delayed until the latter part of the logging, and the sale was ompleted using a helicopter for yarding. This modification to the original contract as done with the approval of the Forest Service. The logging was done with a Boeing ertol-107 helicopter, which has a load capacity of approximately 8,000 lb (3,629 kg). he helicopter logging subcontractor received approximately $90 per M bd.ft. ($19.89/m³) o get the logs to the deck. This cost is higher than the average balloon logging cost, ut with the difficulty of the logging sets, it was felt to be justified. Also, the roduction with this size helicopter is about 100 M bd.ft. (452 m³) per day, which is pproximately three times the balloon daily production; thus, the logging was completed xpeditiously.

Based on the comparison of the helicopter and balloon logging, Boise Cascade decided o sell their balloon logging system and bought their own helicopter. This decision was ased on the Forest Service plans to require aerial logging on substantial volumes of imber in the southern Idaho Batholith. Evidently, Boise Cascade believed that owning heir own helicopter would be more economical--the production would be much greater and he helicopter would be a more flexible system as compared to the balloon system in the daho Batholith.

Table 2.--*Yearly balloon logging statistics*

Year	Timber removed M bd.ft. (m^3)	Percent productive hours[1]	Turns per productive hour	Pieces per productive hour	Balloon yarding cost $/M bd.ft.[2] ($/m^3)	Total cos to get lo to deck $/M bd.ft ($/m^3)
1971	3,533 (15,986)	67.0	5.30	14.99	47.44 (10.48)	62.78 (13.87)
1972	6,290 (28,462)	67.3	6.08	17.59	42.44 (9.38)	58.33 (12.89)
1973	3,233 (14,629)	70.6	5.27	20.75	54.49 (12.04)	72.37 (15.99)

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[1] Total yarding hours including delays divided by total hours logged by yarder times 100.

[2] Balloon yarding cost including landing and road change costs.

[3] Total cost to get the logs to the deck (this includes cutting, yarding, road changes landings, slashing, mobilization, administration, and bedding costs, but does not inclu stumpage costs).

The helicopter system of logging is a high consumer of fuel compared to balloon logging. This could lead to a relative change in the economics of helicopter logging, if fuel prices continue to rise or if fuel shortages occur.

At present, the balloon system would appear to have applications in areas of the Rocky Mountains where the terrain is not as dissected as Anderson Creek and timber volumes per acre and average piece size are sufficiently large to justify this system economically. The use of clearcutting harvesting techniques would help raise volume per acre when environmentally sound. However, for this sale, the need for an overstory removal harvesting technique made the economics of balloon logging marginal when compar to prices received for finished timber products.

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